UNIVERSITAT POLITÈCNICA DE CATALUNYA
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DEGREE IN TECHNICAL ARCHITECTURE AND BUILDING

FINAL DEGREE PROJECT

FIRE SPREAD ACROSS INNER COURTYARDS FAÇADES

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Directors: Dr. Ana María Lacasta Palacio
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Call: April 2020

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To those directly affected by COVID-19,
to relatives, acting groups and the community

SUMMARY

The present work aims to study the spread of fires on inner courtyard facades. It begins with the collection and thinking about the information related to the spread of fire in inner courtyards that has been found in the recent technical literature. A set of real cases are analysed and studied; to continue to the computational modelling of a paradigmatic case. Next there is a detailed summary of each chapter.

The first chapter deals with the spread of fire across the inner courtyards, taking as a starting point what the scientific community has established regarding the movement of smoke in buildings. There are three types of inner courtyards: Airy patio, light patio and inner courtyard of the block. The guiding thread is the exposition of real cases and the analysis of the treatment that the CTE makes of this problem from the point of view of the fire service.

The priority in case of a housing fire is the rescuing of people, and secondly the extinction. For this reason, it deals with the relationship between the inner courtyard and the staircase due to the direct repercussion of the security in the evacuation of people.

The second chapter presents fourteen cases of fire, all of which took place in Barcelona and the Metropolitan Area from 2007 to 2019. These are cases in which the spread of fire across the inner courtyard and/or box enclosure scale has played an important role in the development of the fire. One of these cases, Case 14, has been dealt with more depth in Chapter 3.

The third chapter is a continuation of the study of case 14 that is analysed in the second chapter. Its analysis is based on the computer modelling and simulation of fires with the Fire Dynamics Simulator (FDS) program. After collecting data of the building and of the circumstances of the fire, a geometric model has been constructed that reproduces the actual geometry of the building, the existing furniture, the location of the openings and the calorific properties of the materials. It was a light patio, two small airy patios and a protected staircase with the adjoining parts of the four buildings affected by the fire were modelled.

The general conclusions of the study are established when the previous chapters are completed. There are two areas of conclusions and some final recommendations. The conclusions of the analysis on the spread of fire and its real effects are explained. The conclusions of the computational analysis of FDS program about case 14 are presented. Finally, some recommendations are established in order to improve technical and functional parameters on inner courtyards.

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GLOSSARY

Attic floor: Top floor that is removed from the fronts of the building.

Block: A set of urban plots inside on the same perimeter delimited by the arrangements of the road and public open spaces.

Catalan façade: The usual façade wall in Catalonia is made up two layers of brick with a cavity, with or without covered by mortar. The exterior layer is made by a brick wall and the interior by a hollow brick partition.

Commercial use: Buildings or establishments who sale products or services directly to the public: shops, department stores, shopping malls, markets, shopping malls, etc.

Diogenes Syndrome: Behavioural disorder that usually affects elderly people living alone. It is characterized by total personal and social abandonment and by voluntary isolation in one's own home, where they often accumulate large amounts of household waste.

Equipped fire pump: Set consisting of a valve, a hose and a lance, which is used to transport and project water from a fixed point in a water supply network to the site of a fire. It includes support elements, pressure measurement and protection.

Evacuation height: Maximum difference in elevation between an evacuation place and the corresponding building exit.

Fire load: Heat energy provided by all combustible materials contained in a defined space (it can be expressed per area or volume).

Fire officials: Each of the firefighters available, at a given time, for a performance.

Fire sector: Separate space in a building delimited by fire-resistant construction elements for a certain period of time. Fire can be confined inside so that it cannot be spread to another part of the building.

Fire: Combustion characterized by an emission of heat with smoke, flames or both. Quick combustion that spreads uncontrollably in time and space.

Functional sector: Group of resources and/or staffs with a mandated task, which have a manager and own communications. It has a general scope of action that occupies different geographical sectors.

General Operations Area: Geographic area or location where emergency response activities are carried out or where they are expected to be placed.

Geographic sector: Geographic grouping of work teams, resources or vehicle meeting points to keep the control section at a manageable level.

Housing: Building or area destined for permanent accommodation in apartments.

Jamb: Each of the two sides of an opening, on wich rests the lintel or arch.

Jet of water: Water projected by means of a lance in the form of a compact current.

Rescue hood: Equipment that is placed on the head of the person to be rescued and connecting it to the inverted fork or connection for 2nd user of the firefighter's air equipment, allows to escape of smoky environments. This is an unsealed equipment.

Mezzanine floor: A low-ceiling floor between two others, usually immediately above the ground floor.

Face mask: Disposable mask made of filter material that protects against particles, gases and steams. Their filtering capacity is determined by the class to which they belong.

Premise: Separate or independent enclosure in which activities are carried out which activities take place dependent on a company or institution. The site is inside a building.

Protruding elements: These are the passable built elements, which protrude from the planes of the facades of a building from the first floor. They can be closed or open.

Public residential use: Building or establishment for temporary accommodation: hotels, hostels, residences, etc.

Publics buildings: Building or establishment intended for any of the following uses: cultural, catering, entertainment, meeting, recreation, sports, auditoriums, religious, passenger transport, and similar characteristics.

Slide ladder: Ladder formed by two or three sections that slide on top of each other, which allows it to be more or less long.

Smoke: Visible set of solid and liquid particles suspended in the air, or in volatile products, resulting from combustion or pyrolysis.

Staff: Set of human and material resources that make up a fire truck.

Staffing: The number and level of training of personnel deployed on an emergency.

Staircase well: The central space of the staircase around which revolve the flights of stairs that delimit it.

Staircase: Section or sections of staircase including perimeter walls, landings, handrails and other necessary supports.

Swollen: Increased volume of a material due to heat input.

Thermal camera: Device that by means of infrared rays allows to see in calorific points without visibility.

Turntable ladder: Conceived to access to fires occurring at height using a large telescopic ladder, where conventional ladders carried on conventional appliances might not reach.

Water Line: A set of hoses connected in succession to carry the extinguishing agent from the point of supply to the place where it is to be used.

ACRONYMS

ACM: Aluminum Composite Material.

CAF: Compressed air Foam System.

CEE: Economic European Comunity.

CFD: Computational fluids Dynamics.

CGE: Centre de Gestió d'Emergències de Bombers de Barcelona.

CM: Building study case named "Casa de les mantes", on 64 Sant Pere Més Baix St.

CMA: Corporació Catalana de Mitjans Audiovisuals.

COAC: Col·legi d'Arquitectes de Catalunya.

COEIC: Col·legi d'Enginyers Industrials de Catalunya.

DB CTE-SI: Documento Básico del CTE de Edificación sobre Seguridad en caso de incendio.

DGPEIS: Direcció General de Prevenció, Extinció d'Incendis i Salvaments de la Generalitat de Catalunya.

EPS: Expanded Poliestyren.

EPSEB: Escola Politècnica Superior d'Edificació de Barcelona.

ETIC: External thermal insulation composite Systems.

ETSAB: Escola Tècnica Superior d'Arquitectura de Barcelona.

FDS: Fire Dynamics Simulator.

HOTEL: Hotel building study case on 62 Sant Pere Més Baix St.

HPL*:* High-pressure laminate.

HRR: Heat release rate.

HRRPUA: Heat release rate per area.

ISPC: Institut de Seguretat Pública de Catalunya.

ITeC: Institut de Tecnologia de la Construcció de Catalunya.

JG55: Apartments building study case on 55 Jaume Giralt St.

JG57: Apartaments building study case on 57 Jaume Giralt St.

LOE: Ley Orgánica de la Edificación.

NBE-CPI: Norma Básica de la Edificación sobre Condiciones de Protección Contra Incendios.

NFPA: National Fire Protection Association.

NTE-IPF: Norma Tecnológica sobre las Instalaciones de Protección contra el Fuego.

OMCPI: Ordenança municipal sobre condicions de protecció contra incendis.

ORCPI: Ordenança reguladora sobre condicions de protecció contra incendis.

PIR: Polyisocyanurate foam.

PUR: Polyurethane foam.

PVC: Polyvinyl chloride.

RD: Real Decreto.

RIPCI: Reglamento de Instalaciones de Protección contra Incendis.

RSCIEI: Reglamento de Seguridad contra Incendios en Establecimientos Industriales.

SCBA: Self-contained breathing apparatus.

SPEIS: Servei de Prevenció Extinció d'Incendis i Salvament de l'Ajuntament de Barcelona.

TL: Turntable ladder.

XPS: Extruded polystyrene .

PREAMBLE

This final degree project begins in September 2019, once I have passed the opposition phase of the 81/19 call for Firefighter Access on the basic scale of the Generalitat of Catalonia fire fighters' service, during the period before the start of the Basic Training Course.

My interest in fire and emergencies, however, begins a few years before. It was around the age of thirteen, when I spent much of the summer connected to the Barcelona Fire Brigade website. In September, I asked my father to take me to a fire station for the first time.

A few months later, on December 28 of 2007, there was a housing fire in Tarragona street, which is the second case that is examined in this project. The fire has a personal significance as a school classmate and a teacher lived in the affected building. When we returned to school after the Christmas break, a group of friends went to see our classmate's home. The image of the stairwell and the light patio completely blackened by smoke left a lasting impression on me.

One day, I realised that I had visited the parks of Barcelona so many times that I should go one step further. I mean, to go to the emergency sites to see them and take pictures. In April 2012, I set up Twitter on my cell phone to be aware of any major fire in my city. Given the easy access to information and images published by digital media and users, I started collecting fire pictures with interests for educational purposes.

The most active part of this season lasted until the end of 2017. At that point, I decided to focus on preparing for the oppositions. In total I have attended about a hundred interventions between fires, explosions, rescues and simulations generating an archive of fourteen thousand photos of which nine thousand of them are mine.

Part of the fire cases studied in the present work are fires that I remember when they happened because they came out in the media and I saved the images in my personal archive. Some others are cases that I have been searched in purpose for this project.

The thirteenth case study is a fire in a premise at Enamorats street. It happened in the morning of December 19th in 2019 when I was still working on this project. At that time, I was on my way to the library to do this work and I decided to go to the fire site to see it from the outside and I had the opportunity to talk to a firefighter on his incoming duty shift.

Case of the simulation

On Tuesday, December 16 of 2014 at 10:07 AM there was a fire in the ground floor of Jaume Giralt St. That morning I had to go to EPSEB to print and submit a project for the subject Installations II. I found out about the fire on Twitter while having breakfast. For this reason, I decided to add the camera to my backpack, just in case.

When I was back on the subway, the latest fire photos posted on Twitter kept showing a column of significant smoke, and that is why I decided to go.

I took the first picture of the fire at 13:28 PM, and the last one at 16:25 PM. The fire service deployment was significant, one of the largest I have ever seen in a housing fire. Fire trucks from the six city fire stations, some with all 25 mm hoses pulled, fire fighters with CAF foam on the pants to the waist, urban guards using face masks, and to add, building materials and machinery due to the works being done on the street to transform it into a single platform. At the scene of the fire there was the physical

presence of the Chief of Day, Chief of Operations Division and Director of Fire, as well as a firefighter who was out of service, and had approached the place to see the scope of the fire.

Five days later, I went back to the fire to see how the interior was affected and take photos. The three affected stores had been covered and the rest of the properties evacuated. The only one that continued to function with relative normality was the adjoining hotel. I went to the front desk to express my interest in seeing the affected inner courtyard. His answer was positive, and a hotel worker accompanied me. We went up the protected stairs to the roof, where I could see and take pictures of the inner courtyard from different levels, as well as one of the rooms affected by smoke and temperature.

Now, I seize the occasion to expand the information on this case and perform a recreation using computer simulation.

Five years after the fire, on Wednesday 27th November of 2019, I came back to visit the buildings that were already rehabilitated with the aim of recognizing the largest number of spaces, taking exterior and interior measurements and photographs.

I was able to access the 1st and 2nd flats of the number 55 and the 1st of the number 57 on the Jaume Giralt St. Once again, the reception of the Music Boutique Hotel gave me free access to the entire building as well as the magnetic card of room 25, from where I accessed to the inner courtyard.

The most special testimony was that of Mrs. Roser, a 1st and 2nd neighbour of number 55, a lively elderly woman. When I knocked on her door she said, who is it? - "I'm a student" - I said. Then she opened the door and I began to explain to her the work I was doing, showing her the images of the fire on my cell phone. - No, I can't see it - she answered.

Far from kicking me out, Mrs. Roser, who was blind, offered me her testimony as a story guided by the sounds, smells, voices, and sensations she had experienced that day. Finally, she invited me to her house and I was able to take measurements with my laser distance meter and take pictures.

I have finally finished this paper eight months later, on April 12nd of 2020. I divided my project in two periods: A first four-month period, before the Fire School started, in which I had full dedication to the cause; and a second four-month period while I have been attending the course and doing the online tasks during the week, and I have been trying to finish this paper over the weekends.

I wouldn't have imagined that as a country we would live the activation of the emergency phase of the PROCICAT plan for pandemics and the declaration of a state of alarm. Well, part of the COVID-19 lockdown to stop the transmission of the virus is also part of this work. And why not say so, it has allowed me to finish it more calmly and better.

INTRODUCTION

Fire spread across inner courtyards is a type of external propagation, that occurs regardless of the interior distribution of the building, because of the flow of smoke and flames across holes that communicate with the outside.

The facades that overlook the street dissipate the smoke and flames into the environment once they go outside. Inner courtyards, on the other hand, are a confined outer space in which smoke and fire behave differently. This type of propagation conditions the intervention of Firefighters from an operational point of view.

The Basic Document about fire safety of the CTE specifies objective parameters and procedures to complete basic fire safety requirements. The DB-SI2 structures the problem of the external propagation in two points: Party walls and facades, and roofs. There is no reference to the inner courtyards.

Scope

This work is the spread of fire across inner courtyards façades through an analysis of the theoretical information, analysis of real cases and the use of computer simulation tools to get conclusions that allow a better understanding of this behavior and progress in solutions.

Main objective of the project

To study the problematic of the fire in inner courtyards.

Secondary objectives of the project

To find out what the scientific community has established in relation to the movement of smoke in buildings.

To define a classification on types of inner courtyards.

To study the treatment of the CTE with respect to the fire spread across inner courtyards.

To analyse a set of real fire cases that are representative of the problems of the inner courtyards.

To make a model that allows to simulate and reproduce a fire case as similar as possible to the real ones.

To propose regulatory measures that will help to limit the fire spread in inner courtyards.

CHAPTER 1- Fire spread across inner courtyards

1.1 Movement of smoke in buildings

Smoke is "The solid, liquid, and suspended gas particles in the air formed during the pyrolysis or combustion of a material, joined with the amount of air displaced or mixed in the mass" (37).

Smoke can behave differently in tall buildings than in low ones. In low-rise buildings the influences of fire such as heat, convection movements, and fire pressures, are generally the main factors that cause smoke movement. The predominant factors that cause the movement of smoke in tall buildings are: The chimney effect, the influence of external wind forces and the movement of air inside the building.

LOW buildings	TALL buildings	
Heat + Convention movements + Fire pressures	LOW Building factors	Chimney effect + Influence of external wind forces + Movement of air inside the building

Table 1. Influence of external wind forces and the movement of air inside the building (35).

Chimney effect

During a fire, the fireplace effect is often responsible for the widespread of smoke and toxic gases in tall buildings (35). This effect occurs when the indoor temperature is higher than the outside air temperature and is characterized by a strong current of air from the first floor to the ceiling of a tall building. A study by the National Research Institute of Canada (NRCC) suggests that most air flows:

1. In vertical wells such as inner courtyards, stairwells and lifts.
2. In vertical direction from floor to floor across smallest openings in the floor and ceiling.

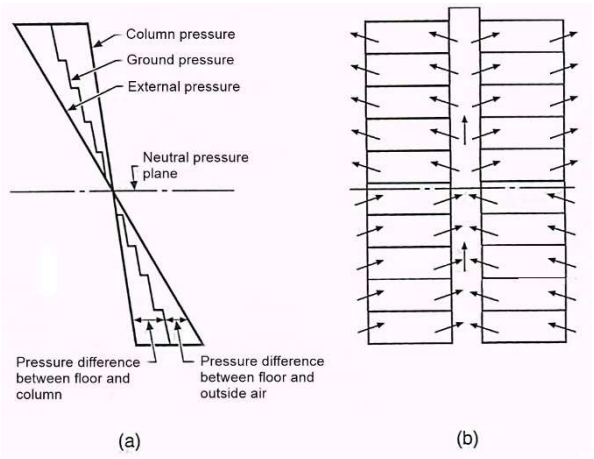


Figure 1. Characteristics of pressure difference of a building subject to the chimney effect (NFPA).

Part (a) of Figure 1 shows the characteristics of the pressure difference of a building in which the chimney effect causes air movement. The slant on the pressure lines represent the differences between regions at the same height.

The air flowing from one region to another is illustrated in the airflow directions represented by the arrows in part (b) of Figure 1.

Influence of outside wind

Wind is another important factor that influences the movement of smoke, which again behaves differently in high and low buildings (35).

The distribution of pressure caused by the movement of an air mass above and around the building (Figure 2) shows that the windward wall is under pressure inside the building while the wall to leeward and both sidewalls, have outward pressure, or suction.

The ceiling of the building has pressure upwards, with its maximum level in the leeward.

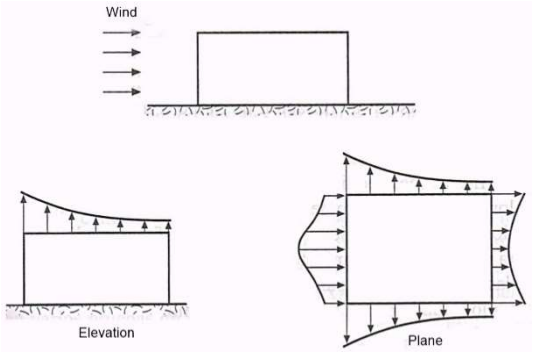


Figure 2. Distribution of air pressure on the four sides and roof of a building (NFPA).

In a low, wide building it will cause a higher volume of moving air over the roof, with a lower volume of air around the sides. A tall, narrow building will push most of the air volume down the path of least resistance around the building, resulting in less air movement over the top.

Wind speed and direction are the main cause of the amount and direction of pressures on the building. The higher the speed, the more influence the following effects will have:

1. Effect of the ground: Wind friction and turbulence at ground level increase in speed as the height increases.

2. Effect of the environment: Presence of buildings and other artificial or natural elements such as trees can produce local effects that may increase, reduce or modify wind direction.

The effect of wind pressures and suction modifies the natural movement of air inside the building. Horizontal pressures and suction can cause the neutral planes to move on the outer walls. Positive wind pressure will tend to raise the neutral pressure plane, whereas negative pressure will lower it.

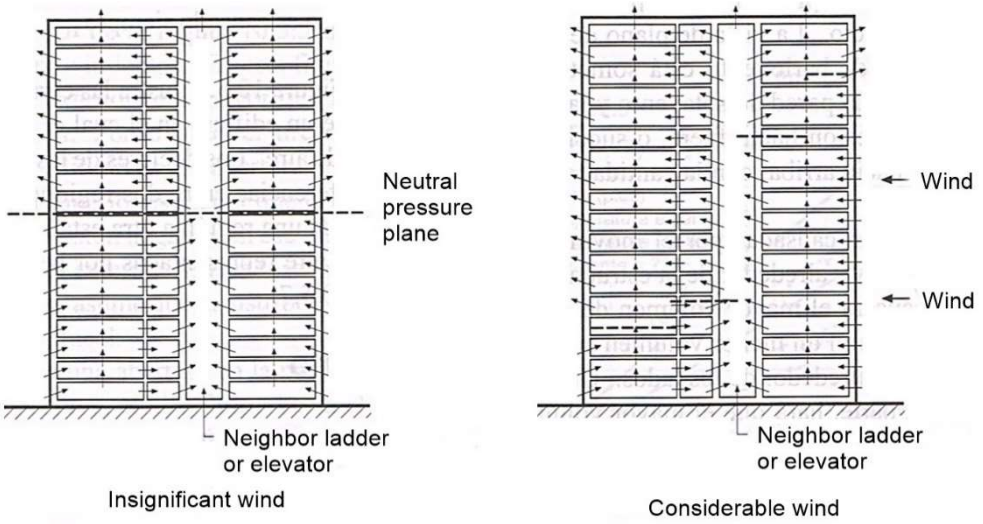


Figure 3. Influence of wind action on air movement in a building. With the presence of significant wind, the neutral plane changes position depending on the area (NFPA).

1.2 Types of inner courtyards

By the term inner courtyard, we can find different types with their own identity.

Based on the approach of the Metropolitan Urban Regulations and the Decree of Habitability 141/2012 on the name of inner courtyards and other names used in the architecture vocabulary, we have classified the inner courtyards into three types: Airy patios, light patios and inner courtyard of block.

1. Airy patio

We define the airy patio as a non-built space located in the volume of the building, of inner or mixed type, intended for ventilation and lighting of kitchens, bathrooms or stairwells (4).

1a. Inner airy patio: These are the ones that do not open to open spaces or roads.

1b. Mixed airy patio: These are opened on one or more sides to open spaces or roads.

Figure 4. Inner airy patio (Verti Vallès).

Figure 5. Mixed airy patio (Author).

2. Light patio

We define the light patio as a non-built space with the same characteristics as the airy patio, destined for ventilation and illumination of parts of the building that are not bathrooms or kitchens (4). As well as that the airy patio, in function of the openness of their sides to free spaces or roads, we can distinguish:

2a. Inner light patio

Figure 6. Light patio of a residential building in Valencia street in BCN (X.Balagué).

2b. Mixed light patio

Figure 7. Mixed light patio of a residential building, in Congrés neighbourhood in Barcelona (Author).

3. Inner courtyard of block

The Inner courtyard of block consists of a central internal core with vertical circulation within it. Cerda's theoretically planned, two or three sided, twenty meter high block lacked profitability and with no strict government controls in place, most of the blocks were soon built up on all four sides while far exceeding their originally planned height.

Figure 8. Inner courtyard of block in the Example neighbourhood in Barcelona (G.Berges).

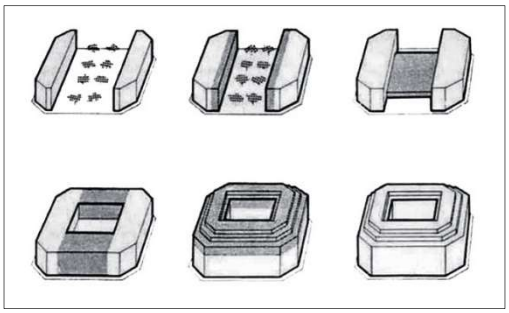


Figure 9. Development of the inner courtyard of block (Failed Architecture).

4. Singular case of the small airy patio

The small airy patio is a courtyard of reduced size used formerly for the ventilation of the bathrooms of the buildings. The size of these courtyards is very small, just enough for an operator to access them for maintenance (Figure 13).

It contains the drainpipes of the ventilated toilets as well as the drainpipes of the building. It is not uncommon to find gas stacks due to their distance with the kitchens of the buildings, as well as individual derivations, which connect the building from the stairs landing.

Figure 10. Small airy patio in a residential building in the Congrés neigbourhood (Author).

Figure 11. Detail of the small airy patio on the roof of the building (Author).

Figure 12. Detail of the small airy patio in the middle of the building (Author).

This type of courtyard was replaced by natural ventilation type Shunt. Subsequently, with the entry into force of the CTE DB HS3, this natural ventilation system must be supported by a mechanical or hybrid aspiration system.

An important part of the city's building park was built before the CTE and, therefore, before the use of natural ventilation type Shunt. In these cases, we can find airy patios of this type.

Figure 13. Access across vertical work (Ver-Tech).

1.3 Problematic of inner courtyards fire spread

The problem of inner courtyards fire spread is a poorly studied topic despite its apparent danger and complexity.

At the state regulatory level, the CTE makes no reference to the problem of fire spread in inner courtyards. Article 10 of ORCPI-08 of the Barcelona City Council “Characteristics of the stairwell and airy patios" develops part of this problem. Depending on the rooms with openings in the inner courtyard and their height, it establishes the inscription of a circle and a minimum surface area.

Despite not being its main subject of study, the technical document “Study on the problems generated by the propagation of fires on building facades” (16) (quoted above) proposes:

"To include in the regulation unique cases that are especially prominent in the spread of fires outside, such as in the light patios and the inner courtyards of block. To treat them as a façade and, given the difficulty of fire teams to access them, to limit the use of materials and products to non-combustible materials, maximum A2-s1, d0".

Passage of facilities extended clothes and other combustible materials

The inner courtyard of block as a vertical element that communicates certain spaces of the apartments of a block of flats, is used frequently to pass the basic supplies of the building and other necessary facilities for the activity of the building. These elements can be the source of a fire or affect it and contribute significantly to the spread of the fire.

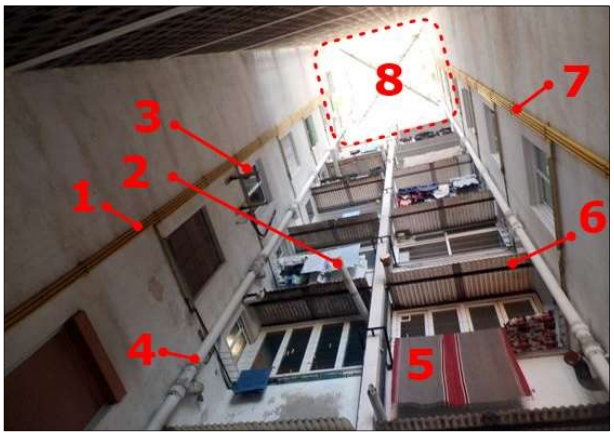


Figure 14. The airy patio of a property located in Ronda de St Pau street in Barcelona (TRAC).

[1] and **[7]** Copper tubing for natural gas.

[2[Evacuation of boiler fumes.

[3] Exterior units of ACC appliances.

[4] PVC pipe drainage.

[5] Flammable textile material on balconies.

[6] and **[8]** Plastic light patios.

Figure 15. The inner courtyard of a building in Aragó street in Barcelona (Som Habitat).

[1] Dry column galvanized steel tube.

[2] Sprinkler installation tubes.

[3] Air pipe conditioning system.

[4] Electrical wiring.

[5] Air pipe conditioning system.

Accessibility and location of the fire

The main operational difference between fires on inner courtyard facades of apartment buildings compared to those on facades facing the street or outdoors is the accessibility.

With the arrival of the Fire Brigade, one of the first tasks of the Chief of Staff is to visually recognize the stage (known as 360°) to know the scene and identify the risks and sensitive points to consider during the intervention.

If the fire breaks across main facade, the location of the affected flat is almost immediate as well as the location of potential victims trapped or congregating on balconies in danger.

The head of the intervention has direct vision on the fire from the moment he arrives, and the fire trucks can be placed in front of the affected property.

If the fire breaks across inner courtyard, the location of the affected floor may be more difficult with no immediate view of the stage. We need to look for an alternative way of access to the affected floor to have an overview, to get a real idea of the stage and to start taking decisions.

In cases where there is a significant smoke column, the interpretation of the smoke during the journey along the way to the fire site may provide relevant information on the development of the fire. The presence of more than one column of smoke indicates that the fire is spreading to more than one way. This can be seen in the examples in Figure 16, Figure 17 and Figure 18.

Figure 16. 2019.06.12 Housing fire in Terrassa, started at 08:25 AM (Nació Digital). We distinguish:

[1] Smoke exit by main façade.
[2] Smoke exit across inner courtyard.

Figure 17. 2019.02.27 Housing fire in Castellvell i el Vilar started at 19:00 PM (Regió7). We distinguish two columns:

[1] Smoke exit by airy patio.
[2] Smoke exit by main façade.

Figure 18. 2019.07.15 Fire in an occupied building in Ciutat de Granada street in Barcelona, started at 12:00 AM (Betevé). We distinguish three columns:

[1] Smoke exit by back façade.
[2] Smoke exit by inner courtyard.
[3] Smoke exit by main façade.

Rescue of people

The rescuing of people trapped in fire from inner courtyard facades is a challenge for fire services. The closed geometry of the inner courtyards often precludes the use of ladder trucks and it is necessary to use manual ladders and urban climbing techniques that test the skill of firefighters. These "in extremis" rescues are associated with a high risk and stress component for the rescue crew.

Figure 19. 2016.07.11 Housing fire in Rodés street in Barcelona started at 09:20 AM with the result of two fatalities. Access via manual ladder (J.Abellan).

Figure 20. 2019.02.06 Housing fire in Paris started at 01:00 AM with the result of ten fatalities. Rescue by inner courtyard façade via manual ladder (B.Moser).

Figure 21. 2019.04.18 Housing fire in Hospitalet started at 06:40 AM with three fatalities. Rescue in extremis through light patio façade (La Vanguardia).

When the fire affects interior airy patios, that is, closed on four sides, the use of a ladder truck for the rescue of people is restricted. The rescuing of people is only possible if they are trapped in areas near facades facing the street. This assumption (Figure 21) is the most complex operating of the following, because if the smoke and heat conditions inside the airy patio get worse, the person will be severely poisoned by smoke.

When the fire affects mixed airy patios openings for some of their faces, that is, opened on one or more sides to open spaces or streets, this may help to dissipate the smoke and heat from the fire and allow timely rescue with a ladder truck.

It will depend on how the courtyard is located, the width of the opening, the distance from the street where the ladder truck is located and the presence of street furniture elements (trees, streetlights, etc.) that make it difficult to pass from the basket of the ladder. In the case of Figure 20, the use of the ladder truck was not possible as the mixed airy patio led to an insufficient width passage to fit the truck.

When the fire affects inner courtyard of block as Eixample neighbourhood, we have again the impossibility of rescues, with escalators, of people trapped in facades of the inner courtyard. In this case, the open space is wide enough to dispel smoke and heat much like when a fire breaks across facade of a building directly facing the street.

We have a more favorable situation with those looking for refuge on the balconies of the inner courtyard of block (Figure 22), as the building's façade can give them some degree of protection against radiation fire in areas where there are no windows.

Figure 22. 2008.12.26 Housing fire started at 09:00 AM in Ferran Agulló street in Barcelona. Rescue of three young people trapped in the inner courtyard of block (CCMA).

Figure 23. 2016.12.09 Housing fire started at 20:15 PM in Passeig Valldaura street of Barcelona. An older marriage trapped on the balcony were rescued (La Vanguardia).

The use of the balcony as a refuge is circumstantial, if the fire is severe enough or the dimensions of the balcony are small, the victims may be in danger (Figure 23).

External fire spread control

The fact that smoke and fire propagate across inner courtyards is a consequence of the open windows and/or the breaking of the window glasses when a certain temperature is reached.

Closed geometry of the interior courtyards often stops the use of the ladder truck for control of outside propagation.

External spread via inner courtyards facades can be controlled from the same inner courtyard by means of the release of water or from neighboring buildings that have openings in the inner courtyard.

Water flush from the base of the inner courtyard is limited to the height of the water jet. Consideration should be given to the risk of falling objects and flammable materials into the inner courtyard which may affect the safety of firefighters.

Throwing water from neighboring buildings is a maneuver that requires a lot of hands to do it; involves the installation of a water installation inside the building from which it is intended to be made. This type of maneuver is initially dismissed as performing direct extinction and rescuing people is already complex enough. In the case of major fires that are expected to be long extinction, then it is more appropriate to mount (Figure 25).

Figure 24. 2019.02.06 Housing fire in Paris started at 01:00 AM with ten fatalities. Control of spread from the inner courtyard (B.Moser).

Figure 25. Windsor Tower Fire. External fire spread controlled since neighboring building (El País).

1.4 Relationship between inner courtyard and stairwell

The spread of smoke and fire across stairwell is one of the causes of deaths in housing fires. The spread of smoke across stairwell is a deadly trap for people trying to get down the street when it is full of smoke.

Figure 26. 2019.03.03 Housing fire in Chile street in Barcelona started at 07:33 AM with the result of two fatalities (La Vanguardia).

Figure 27. 2018.04.28 Housing fire in Pedró square in Barcelona started at 07:30 PM with the result of a fatal victim (D.Guinart).

Figure 28. 2018.04.28 Housing fire in Pedró square (D.Guinart).

Smoke occupancy of the stairwell is an inevitable event in cases where the stairwell and the inner courtyard are part of the same enclosure. In this case, the propagation of smoke and fire can occur, among other things, across the windows of the flats with rooms that face the airy patios.

When the stairwell enclosure has only the access to doors to the residences, the spread of smoke and fire across the stairwell may be preventable as if the occupants of the burning floor close the door at the time to evacuate.

Doors of access to flats cannot be considered as EI doors, because they are under the control of the users of each flat and there is no guarantee that they will remain in the automatic closing time. In some cases, these doors have failed or are nearly collapsing because of heat and flames. In other cases, they have maintained enough stability (E) and thermal insulation (I) to resist the duration of the fire.

Figure 26: A virulent fire declared at dawn burns the entire floor causing the death of the two people staying on the floor. Despite the spectacular flames, the closed door did not cause any personal harm to any other inhabitant or materials to any other part of the building, as declared by the Day Fire Chief Barcelona.

Figure 27: The fire on the second floor causes a mortal victim who despite be safe at third floor, decide to run upstairs to the rooftop. When the fire crews arrived, they heard the cry of help of the victim who couldn't leave when they found the roof door locked.

The intense flames coming out of the door of the second-floor apartment prevented, in the first minutes, that the staff could cross the landing to reach the victim. Meanwhile, on the other apartment on the second floor, which had the front door facing the one on the burning floor, this was enough to ensure the confinement of two elderly people who were saved.

Each case of fire is different and with conditions that are not always comparably, however, the importance of confinement is clear in cases where there is smoke on the stairs and of closing ALL doors to make it difficult for the fire to generalize.

Buildings before the CTE

In the buildings for housing prior to the regulation of the CTE we can find configurations in which the stairwell and the inner courtyard communicate in a direct way. Here there are some of the configurations we can find:

- Stairs with openings in the airy patio: Communication across the windows.
- Stairs linked to the airy patio enclosure: The stairwell and the airy patio form a single space (Figure 29 and Figure 30).
- Stairs with airy patios: The interior space between the sections of the stairs is free from the lower level to the upper one, making a very high empty space (Figure 31).
- Stairs of different buildings that communicate with each other: This is the case of buildings that have more than one neighbor stairwell connected to each other by landings and with exit to the outside by a single portal.

As we have seen, the lack of sectored stairwell enclosures creates many security issues for evacuation of occupants and makes easier the spread of fire**.**

Figure 29. Airy patio used as a stairwell (Ll.Vandellòs).

Figure 30. Stairwell linked to the inner airy patio (Author).

Figure 31. Stairwell (Grupo Excelsior).

Buildings with sectored stairwell

In protected and specially protected stairwell buildings, the spread of fire across the stairwell is highly unlikely. The CTE DB-SI3 (table 5.1) indicates the protection conditions that must be met by the evacuation stairs so that in the event of a fire, the occupants can evacuate the building in a safe manner.

Unprotected stairs up to a descent height of 14 meters (descend 4 floors) and protected stairs up to 28 meters (≈ 9 floors) are allowed in residential buildings. The specially protected scale is supported in all cases.

Annex A - Terminology of the CTE

The degree of protection of the protected stairs may be reduced if the provisions of Annex A.

Annex A of the CTE states that evacuation stairs can have permanently open spaces to the outside when they have a minimum surface area of 5A m² per floor, where A is the width of the section of the stairs in meters. When these gaps communicate with airy patio, the floor dimensions of airy patio must allow to inscribe inside a circle of h/3 m of diameter, being h the height of the airy patio.

If we apply this rule to a building with a width of stairs of 1 meter (the minimum for a general use in Residential Housing), we obtain a minimum accumulated opening of 5 m² per floor. If we assume that the building is thirty meters high (10 floors), the diameter of the inscribed circle is 10 meters. In the event of a fire, a 10 x 10 m inner courtyard may reproduce the effect of a fireplace and flood the stairs with smoke, threatening the safety of the evacuation of occupants.

CHAPTER 2 - Case studies

The following is a set of real fire cases where the spread of fire through the inner courtyard and / or stairwell has played an important role in the development of the fire. There are 14 cases ocurred on Barcelona and the Metropolitan Area between the years 2007 and 2019.

CASE 1: Housing fire - Tamarit St - Barcelona - 2007.08.03

CASE 2: Housing fire - Tarragona St - Barcelona - 2007.12.28

CASE 3: Housing explosion - Andrade St - Barcelona - 2008.03.17

CASE 4: Housing fire - Mèxic St - Barcelona - 2008.10.19

CASE 5: Housing fire - Còrcega St - Barcelona 2005.01.12

CASE 6: Housing fire - Castillejos St - Barcelona 2009.12.31

CASE 7: Housing fire - Botella St - Barcelona - 2013.02.07

CASE 8: Housing fire - Mataró St - Sant Adrià de Besòs - 2014.01.17

CASE 9: Housing fire - Bonaventura Muñoz St - Barcelona - 2014.04.06

CASE 10: Housing fire - Llunàs St - L'Hospitalet de Llobregat - 2015.02.15

CASE 11: Façade fire - Pelai St - Barcelona - 2018.10.29

CASE 12: Housing fire - Marquès de Mont-Roig St - Badalona - 2019.01.05

CASE 13: Fire in a ground floor - Enamorats St - Barcelona - 2019.12.19

CASE 14: Fire in a ground floor - C/Jaume Giralt - Barcelona - 2014.12.16

Each case is presented in the form of a summary sheet with the following format:

- First box: Data type service, location, date and time.

- Second box: Number of victims, resources of firefighters in motion, buildings type, regulations on fire protection in force according to year of construction, type of spread observed and plan of the building and the surroundings with the following pictograms for a better understanding:

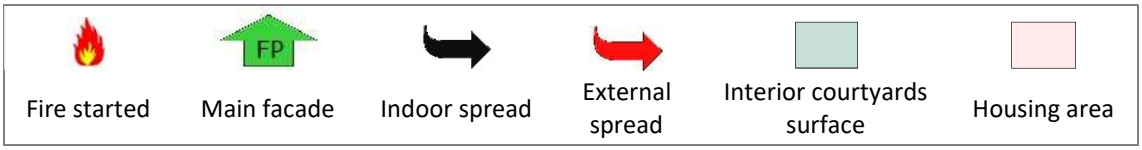


Table 2. Case interpretation legend (Author).

- Brief summary, description of the fire, sources of information and images of the case.

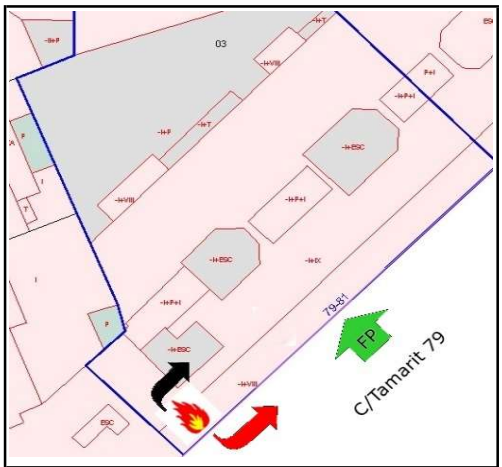
1	TYPE	Housing fire	DATE	2007-08-03	TIME	6:39
	ADRESS	79 Tamarit St	CITY	Barcelona		

NUMBER OF VICTIMS	3 death and 7 injured people
RESPONDING FIRE UNITS	7 units
GROUND FLOOR USE	Commercial
LOFT	No
BUILDING USE	Residential housing
NUMBER OF FLOORS	8
FLATS PER FLOOR	4
YEAR OF CONSTRUCTION	1978
REFURBISH	No
STATE REGULATIONS	NTE-IPF/1974
MUNICIPAL ORDINANCE	Ordinance 1974

MECHANISM OF FIRE SPREADING

Internal fire spread - Stairwell - Chimney effect

External fire spread - Façade - Windows



Ref Catastral 9408303DF2890G0151LX

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork exposed

SUMMARY

The housing fire started on the fifth floor with external flames on façade and smoke-filled in the stairwell. After the fire was extinguished, three people were found dead.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed in a living room on a 5th floor flat, external flames on façade and a smoke-filled stairwell. The fireghters rescued two injured people on the 5th and 4th floor landing; one of them after falling throught the light patio window. The fire spread by the main façade afected the sixth-floor flat partially.

After the fire had been extinguished, during the routine reconnaissance of the building, the bodies of three dead people were found in a seventh-floor flat. The fatalities were one man and one woman found in the floor of the living room) and their son (found in the bathroom of the same flat) who died because of smoke inhalation, that had probably entered the flat through an opened window.

Source: Farenheit 451 - Number 31 and El Periódico.

Main façade of 79 Tamarit St (Avui).

Façade affected by smoke (Avui).

Flames (Farenheit451).

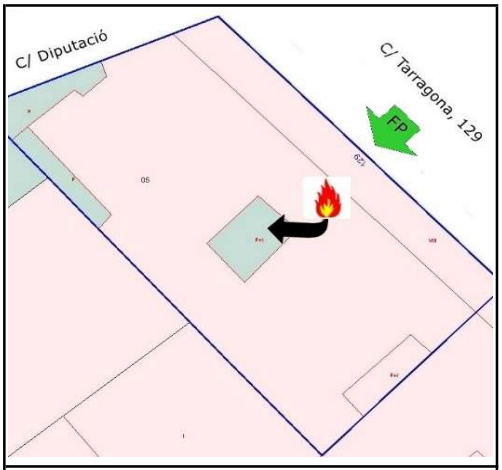
2	TYPE	Housing fire	DATE	2007-12-28	TIME	15:43
	ADRESS	129 Tarragona St	CITY	Barcelona		

NUMBER OF VICTIMS	1 death and 2 injured people
RESPONDING FIRE UNITS	8 units
GROUND FLOOR USE	Commercial — LOFT: No
BUILDING USE	Residential housing
NUMBER OF FLOORS	9 — FLATS PER FLOOR: 4
YEAR OF CONSTRUCTION	1979 — REFURBISH: No
STATE REGULATIONS	NTE-IPF/1974
MUNICIPAL ORDINANCE	Ordinance 1974

MECHANISM OF FIRE SPREADING

Internal fire spread - Stairwell - Chimney effect

External fire spread - Light patio - Chimney effect



Ref Catastral 8612705DF2881B0022YD

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

The housing fire started on the mezzanine floor being fully developed. The flames extended further through the light patio and smoking the stairwell. One of the mezzanine floor tenant wasn't be able to leave and died.

DESCRIPTION

When the firefighters arrived on the scene, the fire was fully developed on the mezzanine's living room and spreaded through the light patio and the stairwell. Due to these, building's electrical, gas, and water service were damaged.

One of the two mezzanine floor tenant decided to leave and left the door wide open. The other mezzanine tenant wasn't be able to leave while tryng to extinguish the fire on a tv screen. The witnesses described that tenant could be seen in the living room through the street window until the shutter dropped.

The other occupants of the building remained at home during extinguishing operations. Firefighters used two hoses of 25mm. Thirty-eight flats were affected to a different extend, and 70 occupants were moved out.

Source: Farenheit 451 - Number 27, El Punt Avui, El País, neighbor-witness and the author-witness.

External flames on the main façade (El Mundo).

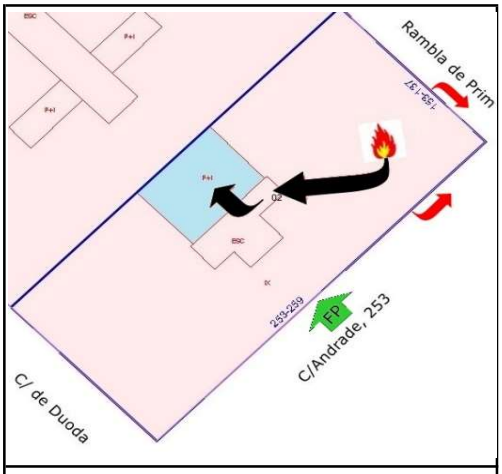
Mezzanine window (CCMA).

3	TYPE	Housing explosion	DATE	2008-03-17	TIME	7:35
	ADRESS	253-259 Andrade St	CITY	Barcelona		

NUMBER OF VICTIMS	3 death and 45 injured people
RESPONDING FIRE UNITS	30 units
GROUND FLOOR USE	Commercial
LOFT	No
BUILDING USE	Residential housing
NUMBER OF FLOORS	8
FLATS PER FLOOR	4
YEAR OF CONSTRUCTION	1960
REFURBISH	No
MUNICIPAL/STATE REGULATION	No regulations

MECHANISM OF FIRE SPREADING

- Internal fire spread - Stairwell - Chimney effect
- External fire spread - Light patio - Chimney effect
- External fire spread - Façade - Windows



Ref Catastral 3759902DF3835H0031EK

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork exposed

SUMMARY

An intentional explosion killed three people and destroyed two flats. Fire spreads through the light patio and the stairwell severely affects the building.

DESCRIPTION

When firefighters arrived, fire was fully developed on the third and fourth doors of the 1st floor and the third door of the mezzanine floor. The explosion had breached the facede wall of the 1st floor to the street.

The tenant of the 1st floor had sprayed the entire flat with a mixture of diesel and gasoline and lost his own life as a consequence of deflagration of gasoline vapor. Two children from the 1st floor died too and firefighters rescued his mother.

Firefighting crews did multiple rescues of trapped occupants using 2 turntable ladders. The other building occupants remained at home during extinguishing tasks accompanied by firefighters. The fire spread through the light patio and the stairwell and it was so extreme that building's electrical, gas, and water service were damaged as well as all flat doors. There was no damage to the structural integrity of the building.

Source: Farenheit 451 - Number 27, El Periódico and CCMA.

Explosion and subsequent fire (CCMA).

Wrecked building (Farenheit451).

Extinguishing and rescue tasks using two turntable ladders (Q.Garcia).

View of the damaged light patio (CCMA).

4	TYPE	Housing fire	DATE	2008-10-19	TIME	1:50
	ADRESS	28 Mèxic St	CITY	Barcelona		

NUMBER OF VICTIMS	1 death and 1 injured people
RESPONDING FIRE UNITS	12 units
GROUND FLOOR USE	Commercial
LOFT	No
BUILDING USE	Residential housing
NUMBER OF FLOORS	5
FLATS PER FLOOR	4
YEAR OF CONSTRUCTION	1973
REFURBISH	No
MUNICIPAL/STATE REGULATION	No regulations

MECHANISM OF FIRE SPREADING

External fire spread - Airy patio - Chimney effect

Internal fire spread - Stairwell - Chimney effect

External fire spread - Façade - Windows

Ref Catastral 8806704DF2880F0007EM

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

A housing fire started on a 1st floor that spreaded through the airy patio affecting eight flats. The flat's tenant died trying to exit trough the stairs.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on the 1st floor, external flames were on the main façade and spreaded through the airy patio.

Firefighters were forced to place fire engines far from the main façade, on Sant Fructuós street, due to the works being done on the street. Extinguishing operations were done throught the stairwell employing two hoses of 25mm. The tenant of the affected flat died while trying to climb the roff of the building thorugh the smoke-filled staircase. His body was found on the landing near the loocked entrance of the roof.

Eight over eighteen flats were afected in a different degree. Gas, and water services were damaged, causing 26 occupants to be moved out from the building.

Source: Farenheit 451 - Number 30, fontdelaguatlla.com and CCMA.

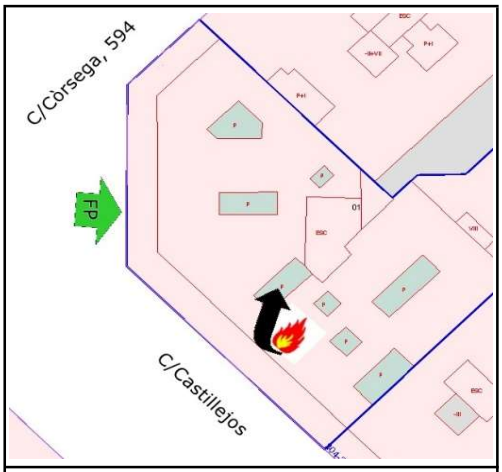
Gas service damaged (Farenheit451).

View of the main facade (EFE).

Airy patio of 28 Mèxic St (Farenheit 451).

5	TYPE	Housing fire	DATE	2009-01-12	TIME	16:15
	ADRESS	594 Còrcega St	CITY	Barcelona		

NUMBER OF VICTIMS	No injuries
RESPONDING FIRE UNITS	11 units
GROUND FLOOR USE	Commercial
LOFT	No
BUILDING USE	Residential housing
NUMBER OF FLOORS	8
FLATS PER FLOOR	8
YEAR OF CONSTRUCTION	1978
REFURBISH	No
STATE REGULATIONS	No regulations
MUNICIPAL ORDINANCE	No regulations
MECHANISM OF FIRE SPREADING	
External fire spread - Airy patio - Chimney effect	



Ref Catastral 1246901DF3814E0034UG

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

The house fire started on a second floor, and spread through the airy patio completely burning three flats and the eight of their galleries.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on the 2nd floor. According to the owner - the fire was caused by the explosion of a television - spreading throught the airy patio going up and down. The fire affects the gas facilities which spreaded fire focus along the eight floor galleries. The seventh attic door was completely burned and building's electrical, gas, and water service were damaged.

Few hours latter, once the fire was extinguished, the flames restarted and completely burnt a 7th floor flat.

Source: Farenheit 451 - Number 31 and El Periódico.


The fire spreads through the airy patio at 594 Còrcega St (Farenheit 451).

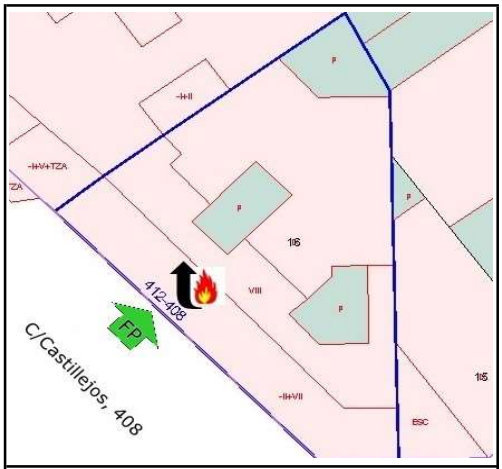

Affected flat at 594 Còrcega St (Farenheit 451).

6	TYPE	Housing fire	DATE	2009-12-31	TIME	4:05
	ADRESS	408 Castillejos St	CITY	Barcelona		

NUMBER OF VICTIMS	4 death and 17 injured people
RESPONDING FIRE UNITS	11 units
GROUND FLOOR USE	Commercial
LOFT	No
BUILDING USE	Residential housing
NUMBER OF FLOORS	7
FLATS PER FLOOR	3
YEAR OF CONSTRUCTION	1963
REFURBISH	No
STATE REGULATIONS	NTE-IPF/1974
MUNICIPAL ORDINANCE	Ordinance 1974

MECHANISM OF FIRE SPREADING

Internal fire spread - Stairwell - Chimney effect



Ref Catastral 0752216DF3805B0001WM

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

A housing fire started on the ground floor and it spread through the stairwell. Four occupants died while trying to leave going down the smoke-filled stairwell.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on the ground floor. The fire had burnt a room, the corridor and a living room of the flat. The spread of smoke and flames throught the stairwell affected all landing floors. The members of the first fire crew, found the bodies of four dead people along the flight of steps. They were occupants of the 4th floor who, instead of remaining at home, tried to leave throught the smoked stairwell. A fifth occupant find refuge in a neighbor flat while going down the stairs.

The two occupants of the burnt flat toke refuge in a light patio balcony and were rescued by firefighters without injuries. The other occupants of the building remained at home during the extinction tasks, following the firefighters instructions.

Source: Farenheit 451 - Number 34, ACN and CCMA.

Main façade 408 Castillejos St (El País).

Stairwell afected by smoke (Betevé).

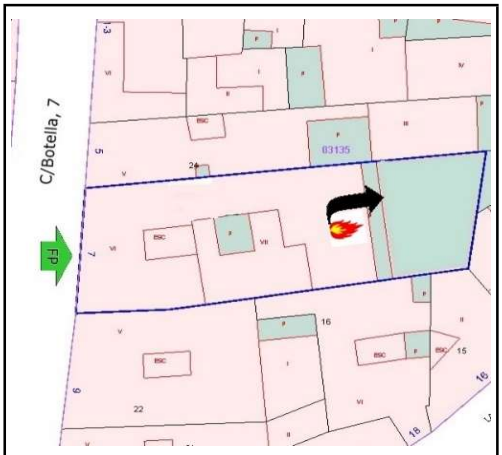
Impact on the stairwell enclosure. Mezzadine landing (Farenheit 451).

7	TYPE	Housing fire	DATE	2013-02-07	TIME	15:43
	ADRESS	7 Botella St	CITY	Barcelona		

NUMBER OF VICTIMS	7 injured people
RESPONDING FIRE UNITS	8 units
GROUND FLOOR USE	Public concurrence — LOFT: No
BUILDING USE	Residential housing
NUMBER OF FLOORS	6 — FLATS PER FLOOR: 2
YEAR OF CONSTRUCTION	1900 — REFURBISH: 2000
STATE REGULATIONS	No regulations
MUNICIPAL ORDINANCE	No regulations

MECHANISM OF FIRE SPREADING

External fire spread - Inner courtyard block - Windows



Ref Catastral 0313523DF3801C0010XH

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

The housing fire started on the 3rd floor, it spread through the inner courtyard block and it completely burnt ten flats and two ground floors.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on the 3rd floor with fire spread through the inner courtyard of the block and the fire focus along all building galleries. During the extinction tasks, a fire crew kept close to a group of eight neighbors refugied on the roof.

Ten of the eleven flats were afected in a different degree, and two of these completely burned. On the ground floor, the fire progressed inside a musical bar burning a soundproof rooom located at the back. Firefighters worked to remove the soundproof wall panels to locate and extinguish the fire.

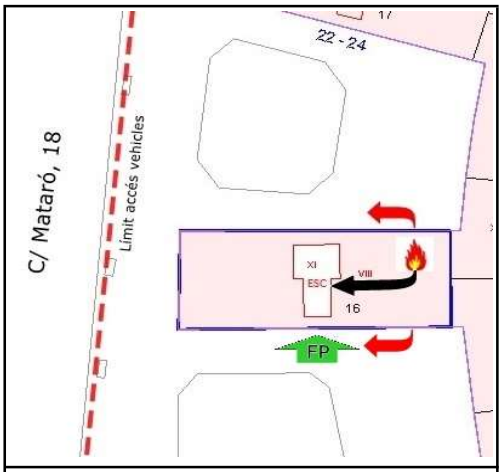
Source: Annual report Barcelona Fire Department 2013, La Vanguardia, CCMA and Betevé.

Fire spreading on the inner courtyard of the block (CCMA).

Fire engines on Botella street (Farenheit 451).

8	TYPE	Housing fire	DATE	2014-01-17	TIME	2:53
	ADRESS	18 Mataró St	CITY	Sant Adrià de Besòs		

NUMBER OF VICTIMS	2 death and 14 injured people
RESPONDING FIRE UNITS	16 units
GROUND FLOOR USE	Commercial — LOFT: No
BUILDING USE	Residential housing
NUMBER OF FLOORS	7 — FLATS PER FLOOR: 4
YEAR OF CONSTRUCTION	1970 — REFURBISH: No
STATE REGULATIONS	No regulations
MUNICIPAL ORDINANCE	No regulations



Ref Catastral 4262916DF3846A0015US

MECHANISM OF FIRE SPREADING

Internal fire spread - Stairwell - Chimney effect

External fire spread - Façade - Windows

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

A housing fire started on the 3rd floor and it spread through facade and the stairwell. Many occupants were trapped and two of them died. The smoke-filled stairwell and the architectural barriers located close to the façades difficulted the firefighting operations.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on the third doors of the 3rd and 4th floors. Firefighters immediately realised that the fire had reached floor 7th and had involved one flat more. The tenant of the third door of the 3rd floor suffers from Diogenes syndrome and there was a high fire load density.

The door of the flat in the highest floor was possibly opened, hence promoting a chimeny effect that could have contribute the quick fire spread. This extreme fire behavior phenomena made flames throught the stairwell from third to seventh floor, that burned doors on all landed floors. Fighfighters extinguish the fire using two hoses of 25mm.

Turntable ladders couldn't be placed because front and rear facades were inaccessible. Only one occupant was rescued by this mean after cutting some tree branches. During the extinction tasks, fire crews remained close to the occupants confined on their apartments. Two fatalities occurred as a result of the fire: The tenant of the 7th floor and an elderly woman on the 6th floor.

Source: Info Bombers Number 34 and CCMA.


Fire spread through the façade (CCMA).


Fire on the 3rd floor (InfoBombers).


Affected flats on the third, forth and seventh floor (CCMA).

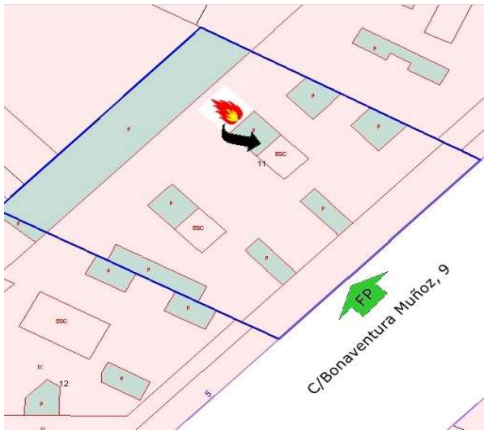
9	TYPE	Housing fire	DATE	2014-04-06	TIME	15:00
	ADRESS	9 Buenaventura Muñoz St	CITY	Barcelona		

NUMBER OF VICTIMS	No injuries
RESPONDING FIRE UNITS	5 units
GROUND FLOOR USE	Commercial — LOFT: No
BUILDING USE	Residential housing
NUMBER OF FLOORS	7 — FLATS PER FLOOR: 8
YEAR OF CONSTRUCTION	1960 — REFURBISH: No
STATE REGULATIONS	No regulations
MUNICIPAL ORDINANCE	No regulations

MECHANISM OF FIRE SPREADING

External fire spread - Airy patio - Chimney effect

Internal fire spread - Stairwell - Chimney effect



Ref Catastral 0313523DF3801C0010XH

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

A housing fire started on the 3rd floor spread through an airy patio and affected one of the two building stairwells.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on 3rd floor and spread through the airy patio. All first and third door flats were afected in a diferent degree as well as the B stairwell. The gas service was damaged.

The building has two stairwells A and B linked throught their landings. The effect of the vertical suction smoke filled stairwell B and cleaned stairwell A. The occupants of the building left by the free smoke stairwell without getting injured.

Source: Barcelona City Council press office, La Vanguardia and Betevé.

Airy patio linked with the B stairwell throught the windows (Betevé).

The third floor flat burned (Betevé).

Gallery affected by the fire (Betevé).

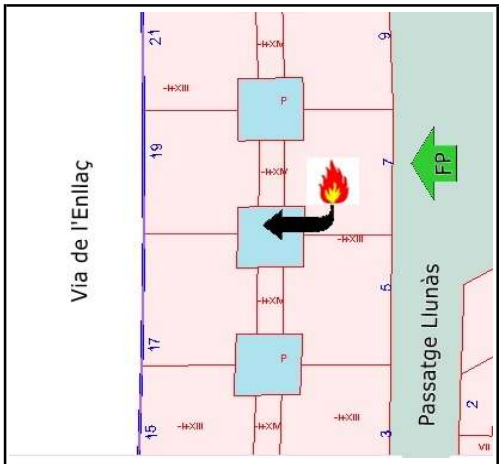
The airy patio lower part (Betevé).

10	TYPE	Housing fire	DATE	2015-02-15	TIME	13:09
	ADRESS	Llunàs St	CITY	Hospitalet de Llobregat		

NUMBER OF VICTIMS	4 injured people
RESPONDING FIRE UNITS	16 units
GROUND FLOOR USE	Residential housing — LOFT: No
BUILDING USE	Residential housing
NUMBER OF FLOORS	13 — FLATS PER FLOOR: 4
YEAR OF CONSTRUCTION	1973 — REFURBISH: No
STATE REGULATIONS	No regulations
MUNICIPAL ORDINANCE	No regulations

MECHANISM OF FIRE SPREADING

External fire spread - Airy patio - Chimney effect



Ref Catastral 3700601DF2830B0456MD

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

A housing fire started on the 3rd floor and it spread through an airy patio and affected the four floor galeries of two different buildings.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on 3rd floor. The fire burnt a room, the flat's kitchen, the flat's gallery and spread through the airy patio. It was smoky and 6-7 meter flames.

There were flaming debris falling and dropping down tended clothes that contributed to spread the fire upwards and downwards the building. Building's electrical, gas, and phone services were burned as well as all galleries. The fire partially afected the kitchen and a room of 6th floor. Firefighters extinguished the fire using five hoses of 25mm.

The effect of the vertical suction kept the stairwell clean of smoke. This fact allowed occupants to leave in secure conditions. Forty-four flats were afected in a different degre, and more than 150 occupants were moved out.

Source: Magazine Bombers.cat #2 and El Periódico.

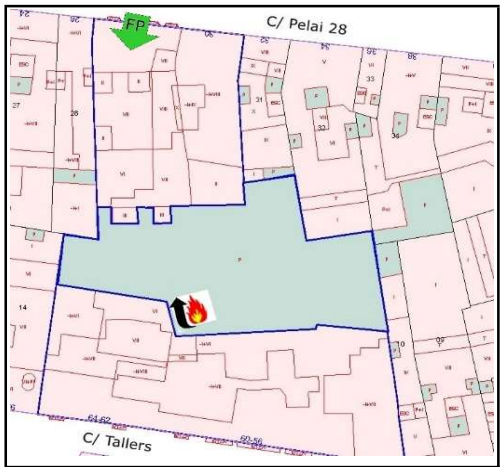
Shared airy patio between blocks number 5 and 7 (Bomberscat).

Building affected (Bomberscat).

Airy patio galleries (Bomberscat).

11	TYPE	Façade fire	DATE	2018-10-29	TIME	9:28
	ADRESS	28 Pelai St	CITY	Barcelona		

NUMBER OF VICTIMS	1 injured people
RESPONDING FIRE UNITS	9 units
GROUND FLOOR USE	Public residential
LOFT	No
BUILDING USE	Public residential
NUMBER OF FLOORS	4
FLATS PER FLOOR	H
YEAR OF CONSTRUCTION	2008
REFURBISH	No
STATE REGULATIONS	CTE DB-SI/2006
MUNICIPAL ORDINANCE	ORCPI-08
MECHANISM OF FIRE SPREADING	
Ex. spread - Inner courtyard block - Ventilation cavity	
TIPOLOGY OF FAÇADE	Ceramic ventilated façade



Ref Catastral 0420935DF3802A0001PO

SUMMARY

Fire started on a ventilated façade located in a inner courtyard block's hotel.

DESCRIPTION

The fire affected the inner surface of the open-joint ventilated façade. The fire spread through the open joints between the panels that compose the outer layer and the smoke attain all façade surface due to the ventilation. The fire was caused during maintenance works on a bituminous waterproofing membrane.

Firefighters extinguished the fire from the lower part of the facade and to the roof of the building. Three fire crews search the rooms to make sure no one else was inside.

Source: Official report issued by Barcelona Fire Department, and El Periódico.


Development of the fire (SPEIS).


The façade arranged at 90 degrees to each other (SPEIS).


Extinguishing tasks on the building roof (Nació Digital).


Point where the fire started (SPEIS).


A smoke affected room (SPEIS).

12	TYPE	Housing fire	DATE	2019-01-05	TIME	9:10
	ADRESS	244 Marquès de Mont-roig St	CITY	Badalona		

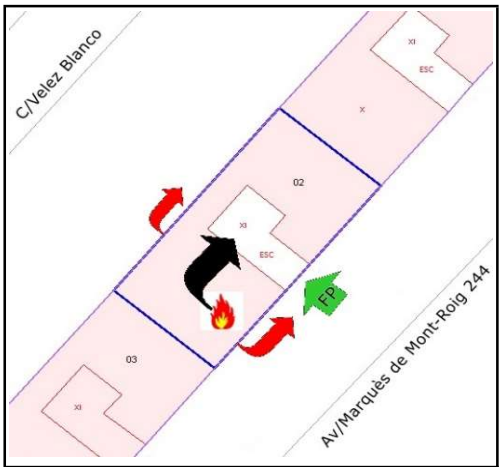
NUMBER OF VICTIMS	3 death and 26 injured people		
RESPONDING FIRE UNITS	16 units		
GROUND FLOOR USE	Residential housing	LOFT	No
BUILDING USE	Residential housing		
NUMBER OF FLOORS	7	FLATS PER FLOOR	2
YEAR OF CONSTRUCTION	1966	REFURBISH	No
STATE REGULATIONS	No regulations		
MUNICIPAL ORDINANCE	No regulations		

MECHANISM OF FIRE SPREADING

Internal fire spread - Stairwell - Chimney effect

External fire spread - Façade - Windows

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar



Ref Catastral 5373502DF3857C0001KJ

SUMMARY

A housing fire started on the ground floor, and it spread across the façade involving upper flats of the building. People from the upper floors tried to escape but they were trapped as the stairwell was full of smoke. Flames came in their flats and three people were found dead.

DESCRIPTION

When the firefighters arrived, the scene on the main façade consisted on: Fire fully developed on a grounnd floor, on a 5th floor, and smoke on a 6th floor. The occupants of a 5th floor were trying to jump from the window. Firefighters used a turntable ladder to rescue 3 adults, 2 children and a baby in an extrem situation. Eleven rescues were made. The extinguishing tasks took place in the 1st, 5th and 6th floor.

The arrival of more support units established a second operational sector on the rare façade, where two occupants had jumped from the windows. Immediate actions were to rescue 5 occupants with the use of the second turntable ladder.

On the second operational sector the fire was fully developed on a eight floor, two fatalities were founded and smoke on a 9th floor, were a third fatality was found. Once the fire was extinguished, five occupants were evacuated by the stairwell using rescue hoods, one occupant from a third flat floor, three from 4th floor and one more from 7t floor.

Source: Return of experiences film - Firefighters of Catalan Goverment, and firefighters-witnesses.

Main façade (CCMA).

Development of the external fire (El Confidencial).

Situation on the rear façade (Diari Badalona).

13	TYPE	Fire in a ground floor	DATE	2019-12-19	TIME	7:45
	ADRESS	45 Enamorats St	CITY	Barcelona		

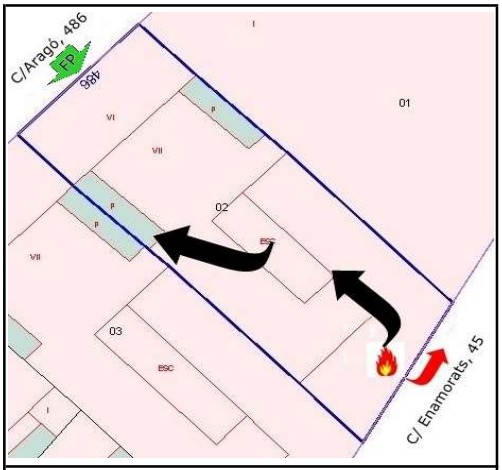
NUMBER OF VICTIMS	26 injured people
RESPONDING FIRE UNITS	15 units
GROUND FLOOR USE	Commercial
LOFT	Si
BUILDING USE	Residential housing
NUMBER OF FLOORS	5
FLATS PER FLOOR	3
YEAR OF CONSTRUCTION	1933
REFURBISH	2007
MUNICIPAL/STATE REGULATION	No regulations

MECHANISM OF FIRE SPREADING

External fire spread - Light patio - Chimney effect

Internal fire spread - Stairwell - Chimney effect

External fire spread - Façade - Windows



Ref Catastral 1641102DF3814B0001KP

TIPOLOGY OF FAÇADE: Catalan façade made by brickwork covered with mortar

SUMMARY

An intentional housing fire started on the ground floor and spread through the light patio, the stairweell and the rare façade. The building suffered partial collapse of two slabs.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on the ground floor of 45 Enamorats St. The fire had spread along the façade to the floor immediately above, causing the attic of the burning premises and part of the roof of the premises to collapse.

The occupants from highest floors had started to leave the building despite the smoke made it difficult for everyone. Firefighters found a lot of victims outside the main entrance of the building who had inhaled smoke. Two occupants jumped from the light patio windows and fell on a plastic skylight cover. A second operational sector rescued people on the main façade using a turntable ladder. Firefighters extinguished the main fire and little focus founded on the flats with opened windows.

Source: CCMA, Betevé, firefighter-witness and the author-witness.

The initial fire (G.Terrafeta).

Smoke-filled light patio (X.Andre).

Rare façade (CCMA).

Groung floor of the housing building (M.Sifre).

Main façade on 486 Aragó St (Nació Digital).

14	TYPE	Fire in a ground floor	DATE	2014-12-16	TIME	10:07
	ADRESS	55 Jaume Giralt St	CITY	Barcelona		

NUMBER OF VICTIMS: 3 injured people

MECHANISM OF FIRE SPREADING	AFFECTED BUILDINGS			
External fire spread - Light patio - Chimney effect	JG 55 [X]	JG57 [X]	CM [X]	HOTEL [X]
External fire spread - Airy patio - Chimney effect	JG 55 [X]	JG57 [X]	CM [X]	HOTEL [ ]
Internal fire spread - Stairwell - Chimney effect	JG 55 [X]	JG57 [ ]	CM [X]	HOTEL [ ]

LENGHT OF SERVICE: 22h 12min since 10:07 of 2014/12/16 to 08:19 of 2014/12/17

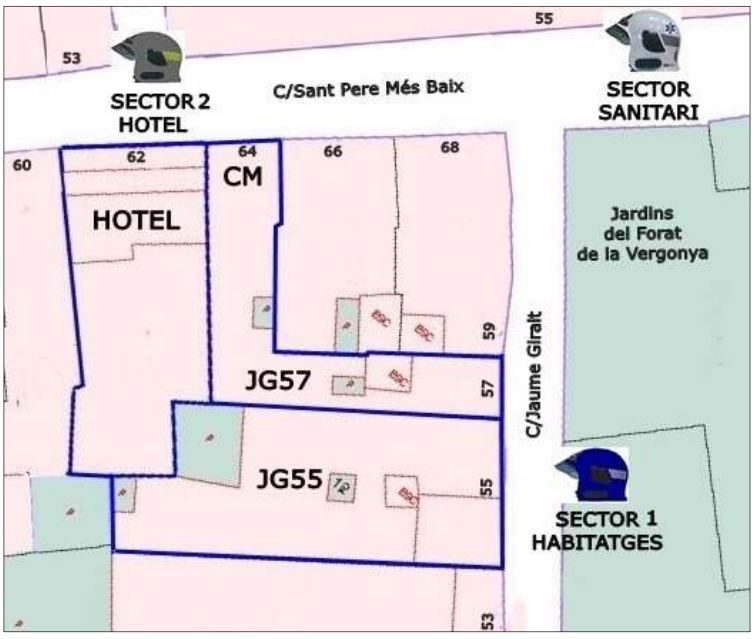
RESPONDING FIRE UNITS 23 units

7	LIGHT FIRE ENGINE B-113, B-122, B-124, B-125, B-127, B-128 i B-129		5	COMMAND UNIT A-00, A-01, A-10, A-20 i A-40	
4	MEDIUM FIRE ENGINE B-316, B-317, B-318 i B-208		2	AIR AND VENTILATION VAN J-09 i J-10	
1	TURNTABLE LADDER E-17		1	DIESEL TANKER J-11	
3	AMBULANCES S-21, S-24 i S-25				

INTERVENTING PERSONNEL 84 people

65	FIREFIGHTERS	1	HEAD OF GUARD
8	CORPORALS	1	HEAD OF DAY
3	SERGEANTS	1	HEAD OF DIVISION
1	SECTOR COMMANDER		DIRECTOR
3	SANITARI TECHNICIANS		

GENERAL OPERATIONS AREA



Graphs: Cadastre, SPEIS and own elaboration.

AFFECTED BUILDINGS

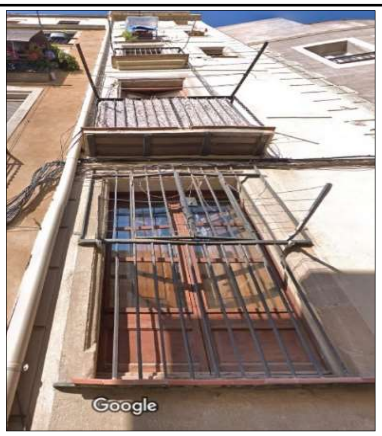
JG55	55 Jaume Giralt St

GROUNG FLOOR USE: Commercial — LOFT: Yes
BUILDING USE: Residential housing
NUMBER OF FLOORS: 4 — FLATS PER FLOOR: 2
YEAR OF CONSTRUCTION: 1860 — REFURBISH: No
FIRE REGULATIONS: No regulations
ESTRUCTURAL AND FAÇADE TIPOLOGY
Floor made by wooden beams and little brick vaults. Catalan façade made by brickwork covered with mortar

Picture: Author.

JG57	57 Jaume Giralt St

GROUNG FLOOR USE: Commercial — LOFT: Yes
BUILDING USE: Residential housing
NUMBER OF FLOORS: 4 — FLATS PER FLOOR: 2
YEAR OF CONSTRUCTION: 1936 — REFURBISH: No
FIRE REGULATIONS: No regulations
ESTRUCTURAL AND FAÇADE TIPOLOGY
Floor made by wooden beams and little brick vaults. Catalan façade made by brickwork covered with mortar



Picture: Google maps.

CM	64 Sant Pere Més Baix St

GROUNG FLOOR USE: Commercial — LOFT: Yes
BUILDING USE: Corresponding with the building JG57
NUMBER OF FLOORS: 1 — FLATS PER FLOOR: 1
YEAR OF CONSTRUCTION: 1936 — REFURBISH: No
FIRE REGULATIONS: No regulations
ESTRUCTURAL AND FAÇADE TIPOLOGY
Floor made by wooden beams and little brick vaults. Catalan façade made by brickwork covered with mortar

Picture: Google maps.

HOTEL	62 Sant Pere Més Baix St

GROUNG FLOOR USE: Public residential — ALTELL: No
BUILDING USE: Public residential
NUMBER OF FLOORS: 6 — NUMBER OF ROOMS: 28
YEAR OF CONSTRUCTION: 2012 — REFURBISH: No
STATE REGULATIONS: CTE DB-SI 2010
MUNICIPAL ORDINANCE: ORCPI-08
ESTRUCTURAL AND FAÇADE TIPOLOGY
Floor made by prestressed concrete beams. Catalan façade made by brickwork covered with mortar

Picture: Google maps.

SUMMARY

A housing fire started on the ground floor that spread through the airy patio and the light patio affecting four buildings. The high density of fire, the age of the building and difficult access required a significant number of fire units. Three buildings suffered structural damages and smoke damage. It didn't cause significant injuries and no major injuries.

DESCRIPTION

When firefighters arrived on the scene, the fire was fully developed on the ground floor of 55 Jaume Giralt St. The smoke filled the stairwell througth the airy patio and spread to light patio affecting the 57 Jaume Giralt St, a building of 57 same stheet a blankets store with mezzanine of 64 Sant Pere Més Baix St (perpendicular to JG St) and the Hotel Musik Boutique on 62 Sant Pere Més Baix St.

The smoke also filled the stairwell of 57 Jaume Giralt St and the fire spread from the airy patio to the rooms in the next building. A few minutes latter, intermittent smoke and flames became visible, spreading from the blanket shop. Firefighters operations were organised in two geographic sectors (Sector 1: Flats and Sector 2: Hotel) and a functional sector (Care Sector).

SECTOR 1: Flats - Commander: Sargeant

Three occupants were rescued on 55JG, a blind woman of the second flat floor and two man of the second and fourth floor 2nd. A dog was rescued on 57JG. On the ground floor there was a high fire load density due to the gazz cilinders and air conditioning equipment. Firefighters extinguished the fire using four hoses of 25mm, two of them with Compressed Air Foam System. Several fire crews searched the flats to ensure that there was no one else inside.

SECTOR 2: Hotel - Commander: Sector Commander

Firefighters extinguished the fire started on the ground florr, the mezzanine and the first floor on 64 Sant Pere Més Baix St (Casa de las Mantas "CM"). The access to the upper floors was made throught the 57 Jaume Giralt St stairwell. This building linked to the 57JG throught the light patio and an airy patio. High temperature and the precarious state of the structure made it difficult to move and work inside the blankets store. The stair vault connecting the gorud floor to the first floor of the store collapsed.

The fire through the inner courtyard, which spread from the protected staircase of the Hotel Musik Boutique, was controlled by hoses of 25 mm. Heavy smoke was detected in six hotel rooms with open-air windows (rooms 15, 25, 35, 45, 55 and 65).

CARE SECTOR - Commander: Sanitari Technician

The three rescued people were treated by the SEM health group. Staff control was also carried out in the recovery area.

At 22:00h the building was searched for Fighfiters and no evidence of fire was found. They used a thermal imaging camera to check the head beams, with no evidence of higher termerature than 20°C. Carbon monoxid mesuraments also resulted negative. A fire unit remained at the site of the large fire throughout the night.

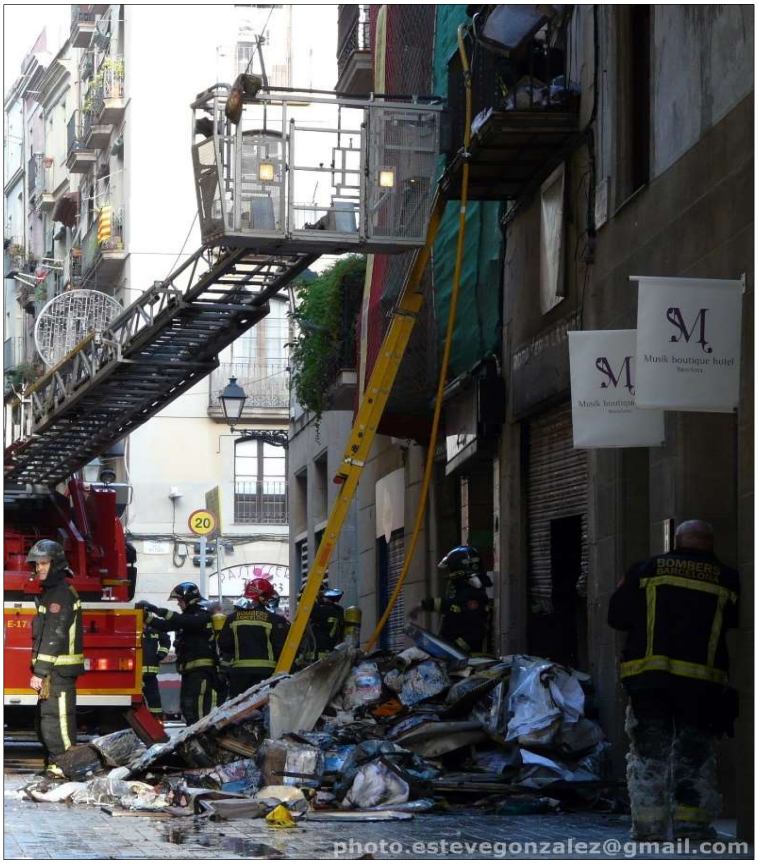
PHOTOGRAPHS OF THE FIRE

2014/12/16 Images of smoke generated by the fire (unknown author).

2014/12/16 Column of smoke from the fire seen from Montjuïc (author unknown).

2014/12/16 Situation of the fire at 13:23 from Sant Pere Més Baix St (Author).

2014/12/16 Access to the mezzanine (Author).



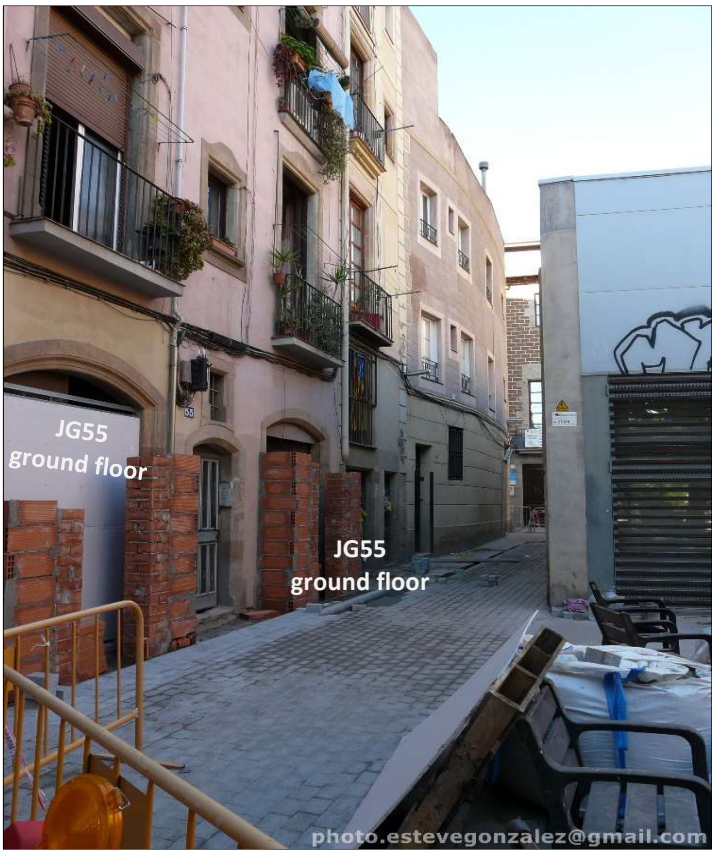
2014/12/16 View Casa de les Mantes and Hotel (Author).

2014/12/16 View Casa de les Mantes and Hotel (Author).

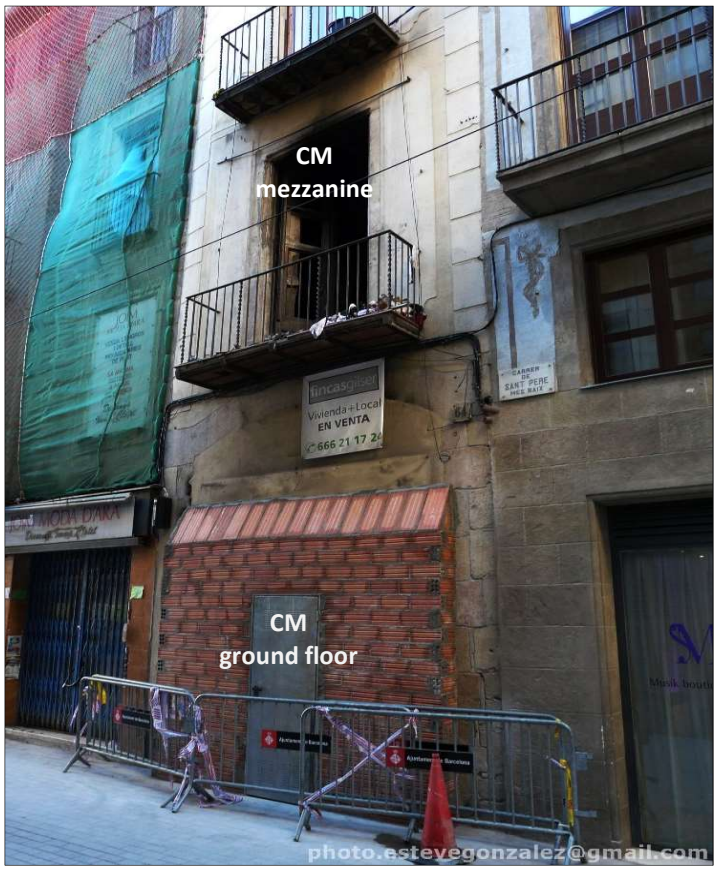
2014/12/16 Material of the interior of the premises at 55 Jaume Giralt St (Author).

2014/12/16 Gazz cilinders inside the premises set on fire at 55 Jaume Giralt St (Author).

PHOTOGRAPHS DAYS AFTER THE FIRE



2014/12/21 Walled ground floor at 55 Jaume Giralt St (Author).



2014/12/21 Walled ground floor at 62 Sant Pere Més Baix St (Author).

2014/12/21 Burned light patio seen from the roof of the Hotel (Author).

2014/12/21 Burned light patio seen from the protected staircase of the Hotel (Author).

2014/12/21 Protected staircase of the Hotel, first floor window (Author).

2014/12/21 Hotel room, flat screen TV impacted by temperature (M.Sellarès).

2014/12/17 Casa de les Mantes, first floor affected (M.Sellarès).

2014/12/17 Casa de les Mantes, first floor affected (M.Sellarès).

2014/12/17 55 ground floor at 55 Jaume Giralt St, origin of the fire (M.Sellarès).

PHOTOGRAPHS OF THE CURRENT STATE

2019/11/27 Renovated daylight seen from room 25 of the Hotel (Author).

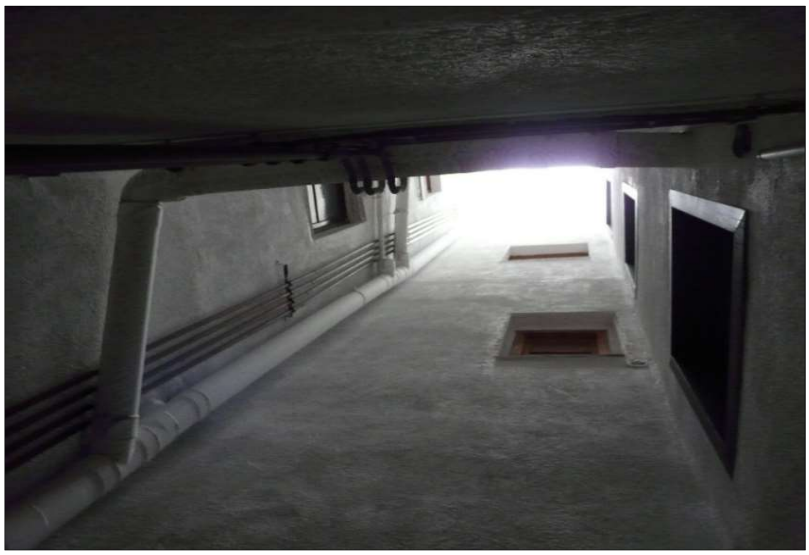
2019/11/27 Renovation of the bedroom of 55 Jaume Giralt St (Author).

2019/11/27 Rehabilitated light patio seen from the protected staircase of the Hotel (Author).

2019/11/27 Refurbishing of Hotel room 25th (Author).

2019/11/27 Small airy patio JG55 (Author).

2019/11/27 TV screen of Hotel room 25th (Author)



2019/11/27 Small airy patio JG57 (Author).

SOURCES

Official report issued by Barcelona Fire Department.
Neighbor-witness of Jaume Giralt, 55.
Witness of two employees from the hotel Musik Boutique.
Author-witness.
Digital press: Barcelona City Council press office, La Vanguardia and Betevé.
Video "Propagación esquematica de incendio" of T.Lucena firefighter.
Pictures: Network, Sergent M.Sellarès and Author.

CHAPTER 3- Computational simulation

3.1 Computational fire simulation models. Fire Dynamics Simulator.

Computational fire simulation models (MSCI) are computer programs that use mathematical models to predict fire behavior. They interpret and analyze their results using auxiliary computer tools. We distinguish two types of models from this mathematical point of view:

Probabilistic models

They evaluate probability of the fire occurring based on the analysis of the likelihood that a fire will occur by analyzing the parameters that influence the fire risk. As a result, the statistical probability of fires is obtained but little or no information is provided regarding on the production and distribution of combustion products.

Deterministic models (5)

They calculate the effects of the fire based on the physical, chemical and thermodynamic relationships, and on the empirical correlation. They can generally be classified into zone models and field models.

a) Computational zone models

Zone models consider that the total volume of the enclosure is divided into two zones or layers with uniform temperature, mass, volume and energy. They allow the incorporation of different combustion models to consider different fire regimes in compartments, that is, fuel-controlled fires and ventilation-controlled fires.

The output variables provided by the zone models are the evolution of the interface between the hot and the cold layers, the evolution of the temperature between these layers, the concentration of O_2 in the enclosure or the transfer of mass and energy through the ventilation holes.

Zone models do not allow to study dynamic pressures caused by fire and/or to obtain a spatial resolution of the temperature field.

Zone models are applicable to cases in which simple geometries are studied where spatial resolution within an enclosure is not important. Its computational cost is lessened, as we can perform a simulation in a few seconds or minutes.

b) Computational field models

Field Computational Fluid Dynamics (CFD) models use a mesh to divide the volume study into thousands of small control volumes called cells. They simulate the movement of any kind of fluid by solving the Navier-Stokes equations which are iteratively solved in each of the cells of control volumes.

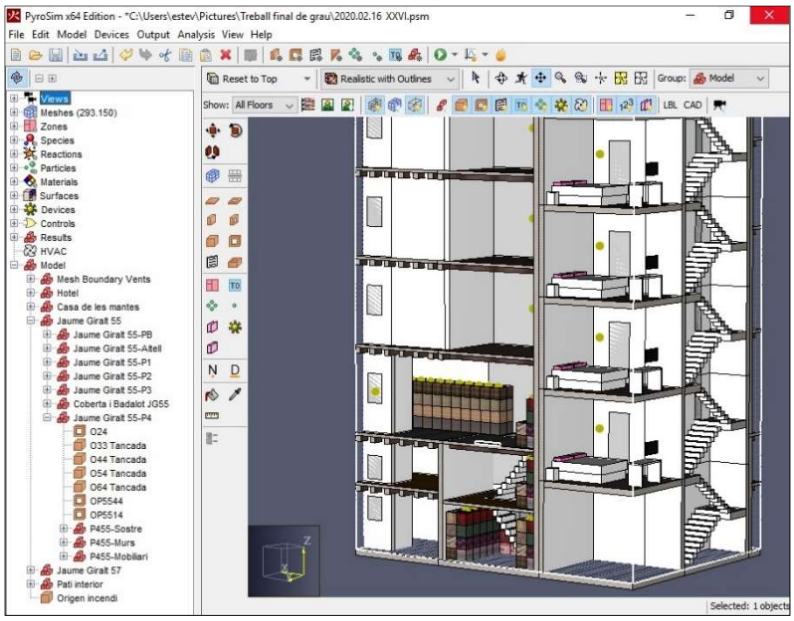
Field models use and study the spatial evolution of system properties using finite volume techniques that allow much more complex geometries to be modelled.

Fire Dynamics Simulator

The case of study has been simulated using the Fire Dynamics Simulator (FDS) and the "Smokeview" visualization program developed by the National Institute of Standards and Technology (NIST) of the US Department of Commerce. Specifically, version 6.7.4. (33).

The first version of the program was released in February 2000. During its development, the FSD has been oriented to solve practical fire problems in fire protection engineering. FDS software is a Fortran program that reads input parameters from a text file. It calculates a numerical solution to equations that control the process and writes user-specified output data to files.

Smokeview is an independent and complementary viewing program that reads FDS output files and produces animations on the computer screen.



PyroSim program has been used to build the case of study, as it is designed to translate the computer language used by the simulator into a more intuitive and graphical interface (43).

It is has been used through an educational license provided by the Department of Architecture Technology of the EPSEB.

Figure 32. View of the PyroSim interface with the model object of study.

The user constructs the building or part of the study object as if it was a three-dimensional graphic model, defining the geometry of the various building elements, the obstructions, the characteristics of the furniture and characterizing the surfaces with the physical properties of the materials.

On the other hand, it allows to incorporate everything related to the characteristics of fire and the loading of solid and liquid fuels. The output data gives information about the movements of the smoke, its velocity, temperatures and levels of CO_2 concentration, and the time it takes to produce flash-over and others.

In relation to the combustion model, for most applications FDS uses a single chemical reaction controlled by the mixture of air, fuel and products. Radioactive heat transfer is included in the model by solving the radiation transport equation for a gas. The equation is solved by a technique like the finite volume methods for convective transport, so that its name is Finite Volume Method. The FDS geometry approximates the governing equations of a rectilinear mesh. Rectangular obstructions are forced to conform with an underlying mesh.

3.2 Sources of information

The case file number 14 of Chapter 2 - Case Study, provides a data set that is necessary to understand the case. The present model reproduces the behavior of the fire just as it happened that day from different sources of information:

GRAPHIC DOCUMENTATION

My own photographs
- Day of the fire (2014.12.16)
- Visit (2014.12.21)
- Visit 5 years (2019.11.27)

Social media and social Networking graphic content
- Video "Schematic propagation of fire" by firefighter T. Lucena
- Pictures Sergean M.Sellarès

Graphic survey
- Electronic office Cadastre
- Taking measurements
- Google Maps satellite

WRITTEN DOCUMENTS

SPEIS Report

Digital press
- BCN City Council press office
- La Vanguardia
- Betevé

WITNESSES
- Neighbor of 55 J.Giralt St (2019.11.27)
- Worker of the hotel (2014.12.21)
- Author

Figure 33. Airy patio sketch (Author).

Figure 34. Electronic office Cadastre.

Figure 35. SPEIS report.

Figure 36. Bcn City Council press.

3.3 Working hypothesis

The model has used all the objectifiable indicators obtained from the different sources of information to reconstruct the evolution of the fire. For example, all windows that appear in the photographs after the fire with the whole glass have been locked by the controller, which provides for the opening when the glass breaking temperature is reached. Apartment room doors have been left permanently open as no information is available. Hotel room doors are permanently closed as this is how they were.

The nuances included in the report of the SPEIS, the testimony of the neighbor of the 1st floor of 55 Jaume Giralt St and the video of the firefighter Toni Lucena have been key to narrowing the point of origin and the probable evolution of the fire which allowed such a wide spread.

The causes of the fire and the exact point of the ignition could not be determined with certainty. What is known for sure is that the fire begins in the lower floors of the JG55 building, most likely in an area near the small airy patio. The first call to the emergency services is at 10:07:30 from a landline phone in this building.

According to the neighbor's testimony, she heard a noise that she initially attributed to the street works. This noise, witch she remember's like a creaking noise "as if wooden twigs were breaking" is increased until she gets the feeling of having it inside her home.

Figure 37. Origin (M.Sellarès & Author).

Figure 38. Fire origin and the situation of the people. Location of the neighbor marked in red.

That's when she gets out of bed, opens the bedroom door, and the small airy patio window breaks, causing the fall of glass broken on her.

She closes herself again in the room, and she calls 112. The woman, who's is blind, tells what is happening to 112 operators without being aware that this is a fire. His call is transferred to 080's call center where he explains the same thing again. The answer was "We have noticed this fire, we are on the way, wait a moment". At this moment she hears the word "fire" for the first time and begins to be aware of what is happening.

Then she goes out of her room again, and this time, she does notice a heavy smoke smell and a heavy heat "as if you were entering in an oven." She decides to confine herself to the dining room standing near the window to make herself visible. In the arrival of the firefighters she is evacuated by stairwell with a rescue hood.

3.4 Modeling

The modelling stage is made up of four buildings that share three types of inert courtyards: A light patio and two small airy patios. The buildings were built between 1860 and 2012, which is why there are major differences between the construction typologies of one and the other.

The interior distribution of floors in each of the buildings and between them is not always homogeneous. This is the case of the access to the floors of 64 Sant Pere Més Baix St, which is carried out through the neighbors' stairs of the 55 Jaume Giralt St, located perpendicular to the main façade.

The free height of the hotel's floors, which is recently constructed, is constant on all floors. However, in the other three buildings, the free height of the homes gradually decreases as we climb to the upper floors. In the face of this de-escalation and to reproduce the composition of the four buildings consistently, it was necessary to model the four entire buildings in every detail, including the interior stairs.

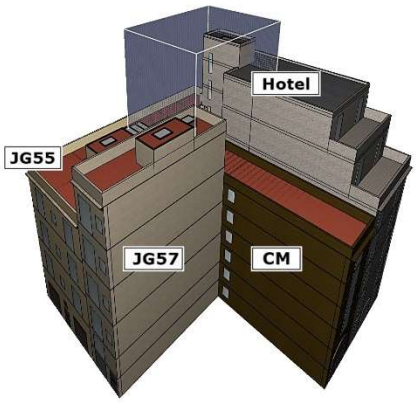


Figure 39. Perspective of the whole model.

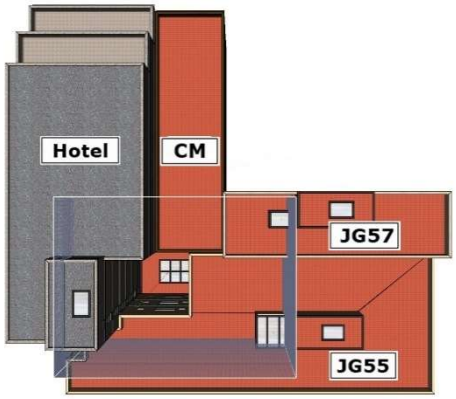


Figure 40. Plant view of the whole model.

Subsequently, a volume of 11.40 x 8.80 x 26.00 m was isolated, encompassing the common elements of the building that contributed most significantly to the spread of the fire; the light patio and the two small airy patios JG55 and JG57.

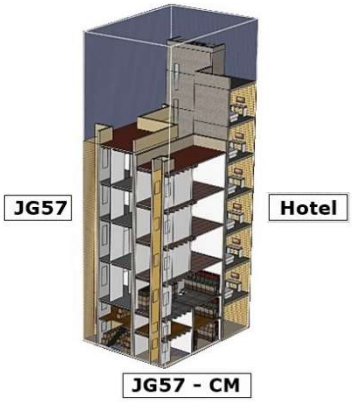


Figure 41. Perspective of the isolated volume.

Figure 42. Plant view of the isolated volume.

Meshes

The size of the cells is important, as it can greatly influence the results of the model. Smaller meshes allow us to obtain more accurate results, but at a higher computational cost.

The selected cell size is 0.20 m which represents a total of 293,150 cells of 0.20 x 0.20 x 0.20 m. Under these conditions, the total calculation time to simulate 774s was 183h15min44s. Also 0.10 m cells were tested but were rejected due to their high computational cost.

The first version of the model was accurate to the actual measurements of the building elements in each building. The wall thickness enclosing walls, partitions, and load-bearing walls reproduced as they were, defining a section of the beams as closely as possible to reality.

The first simulations already showed that the program did not assimilate correctly the geometry of irregular or smaller constructive elements than the cell.

For this reason, the dimensions of the walls, slabs and distances between elements have been adjusted so that all values are multiples of 0.20 m. Rectangular section beams have become square. The partitions and interior furniture of the buildings have kept their real size.

Devices

Thermocouples allow you to capture the ambient temperature of a point. There are two types of thermocouples different depending on the function they perform:

- Thermocouples that monitor the temperature:
  - Thermocouples that monitor the temperature:24 thermocouples to capture the room temperature of all rooms.
  - 60 thermocouples distributed in three columns of twenty, one for each airy patio.

- Thermocouples for actuators that perform pre-set actions when they reach a certain temperature:
  - 25 thermocouples open the windows of the light patio when reaching 200°C
  - 12 thermocouples open the windows of the small a.patio JG57 when it reaches 200°C
  - 9 thermocouples open the windows of the small a.patio JG55 when they reach 200°C
  - 125 thermocouples that ignite the boxes of combustible material when reaching 200°C
  - 42 thermocouples that ignite textile packages at 200 °C

Windows nomenclature

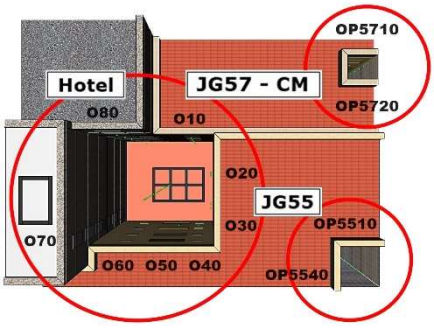


Figure 43. Window's nomenclature.

Window thermocouples are identified by the name of the window. It consists of letters and two numbers. The letters identify the airy patio in which it is located.

O: Window located in the light patio.
OP55: Window located in the small airy patio of JG55.
OP57: Window located in the small airy patio of JG57.

The 2 numeric figures indicate the position in the airy patio using clock position and the floor where it's located.

2D and 3D Slices

Slices and volumes of visualization allow you to reproduce the results in the form of 2D and 3D animation respectively. Both tools have been used in the model to monitor pressure and temperature:

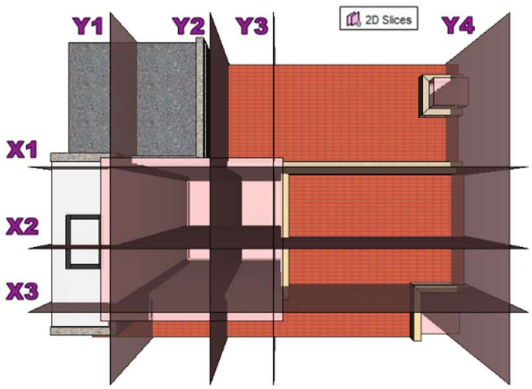


Figure 44. 2D Slices situation.

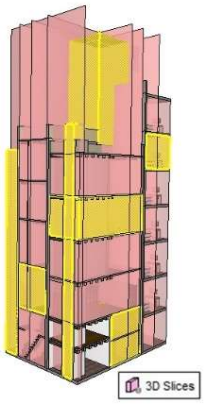


Figure 45. 3D Volums.

2D Slices situation:

Three slices in x direction and three slices in y direction.

3D Volumes situation:

An independent volume for each flat, hotel room, airy patio, small airy patio, light patio and stairwell.

Materials

A sufficient number of materials have been defined to represent the model in a more or less standardized way. In order to ease the understanding of the model, a different hydraulic tile was chosen for each old building. The properties of each of these materials are the generic that are included in the program.

The parts of the model with a 45° striped pattern are sectioned elements.

Concret

Mortar rendering JG55 | Mortar rendering JG57 | Mortar rendering Hotel | Mortar rendering CM | Gravel roof Hotel

Yellow pine

Wooden beams | Parquet floor lofts | Parquet floor Hotel | Wooden furniture

Foam01

Upholstery beds JG55 | Upholstery beds Hotel

Gypsum

Interior plastering's

PVC

TV screens and microwave

Steel

Metallic elements

Tile material

Mosaic tiles JG55 | Mosaic tiles JG57 | Mosaic tiles Hotel | Mosaic tiles CM | Ceramic tile on crossable roofs

Burner

The fire load of the burned areas was simulated using cubes with a burner treatment.

These cubes of 0.40 x 0.40 x 0.40 m are stacked and tied to a thermocouple at the top of each box column. When the temperature reaches 200°C a controller activates them, and they begin to burn, experiencing a linear growth of 100% in 60 seconds. After these 60 seconds, the fire intensity is kept at its maximum until the end of the simulation.

Types of materials

On the ground floor of the JG55 building wooden furniture, electrical equipment, air conditioning machinery, butane gas cylinders, gas pressure vessels and various materials can be found. The exact quantity of each type and their distribution in the premises area is unknown. For this reason, it has been decided to represent the material in the form of boxes of combustible material with a similar distribution throughout the area.

Boxes of combustible material on the basement and loft of the JG55 building.

In the ground floor and in the first floor of the CM building, we can find home textile material stacked on shelves arranged along the wall. This material is represented in the form of packets of blankets.

Packages of textile material on the ground floor and first floor of the CM building.

The combustion temperature as well as the rate of heat release per unit area of the building materials are defined by the program for each of them. For burner treatment materials, these two parameters are set differently:

- Combustion temperature

This decision has been made considering that the temperature values of the materials present in the damaged premises can vary from negative values in the case of the gas stored in bottles to temperatures of 390°C in the case of PVC. The set temperature is 200°C, like the pine wood (250°C) and paper (230°C).

- Heat release rate per unit area (HRRPUA)

This is a complex parameter that has been deduced by applying a trial and error method. It has been started with a value of 450 kW/m² and has been reduced to the minimum required to bring the various packages and boxes into combustion, it's 250 kW/m².

3.5 Results of the simulation

Spread of fire

Graphic analysis of pressure and temperature variations linked to fire events.

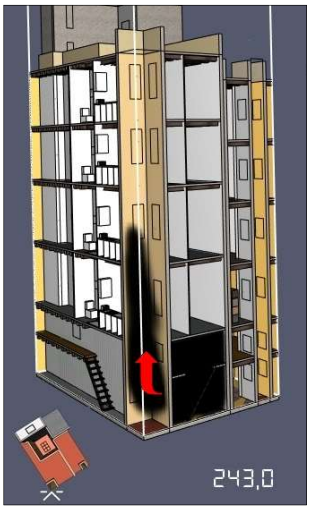


Figure 46. Smoke & flame t=243,0s.

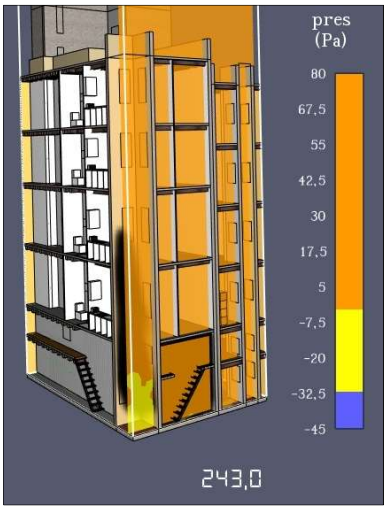


Figure 47. Pressure & smoke t=243,0s.

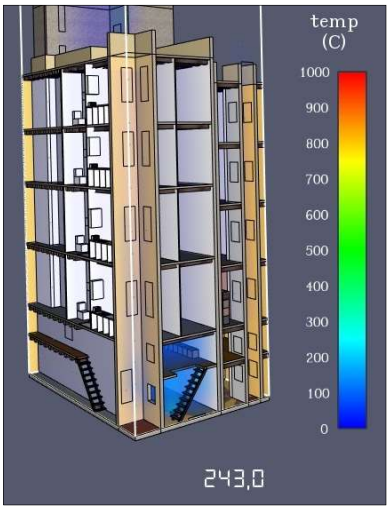


Figure 48. Temperature t=243,0s.

243,0s The window that connects the groend floor 2a with the small airy patio in the JG55 building breakes. **The smoke is sucked out by the fireplace effect through the small airtshaft.**

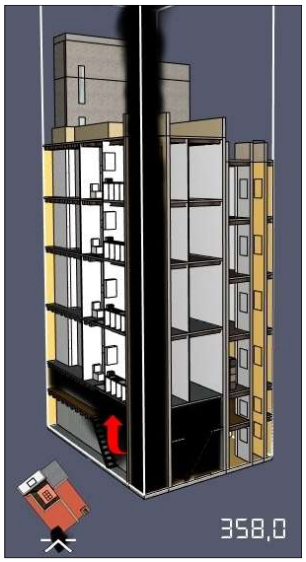


Figure 49. Smoke & flame t=358,0s.

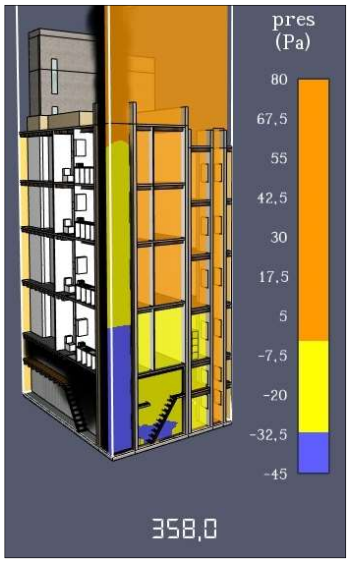


Figure 50. Pressure & smoke t=358,0s.

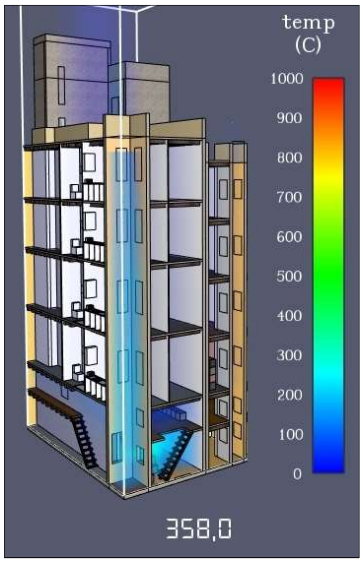


Figure 51. Temperature t=358,0s.

358,0s The gases go up through the small airy patio breaking the windows enabling the entry of **smoke into thze ground floor and the 2nd doors**. The neutral pressure plane of the airy patio is located almost at the highest point of the building.

Figure 52. Smoke & flame t=406,0s.

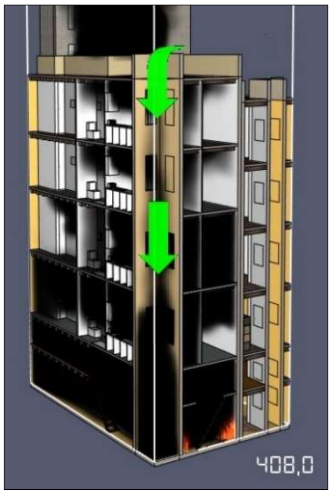


Figure 53. Smoke & flame t=408,0s.

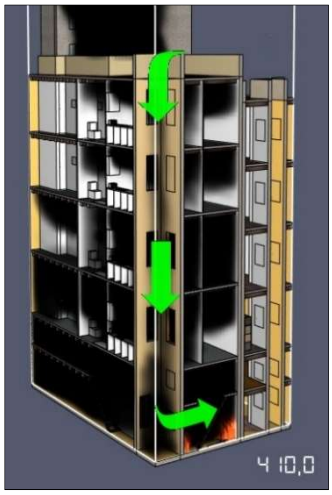


Figure 54. Smoke & flame t=410,0s.

406,0s

The skylight of the light patio breaks down. The exit of smoke and flames through it generates a negative pressure inside the fire which reverses the sense of air circulation through the small airy patio, inducing the general combustion of the whole enclosure. The change in the direction of air circulation through the airy patio causes a drop of temperature, as shown Graph 1.

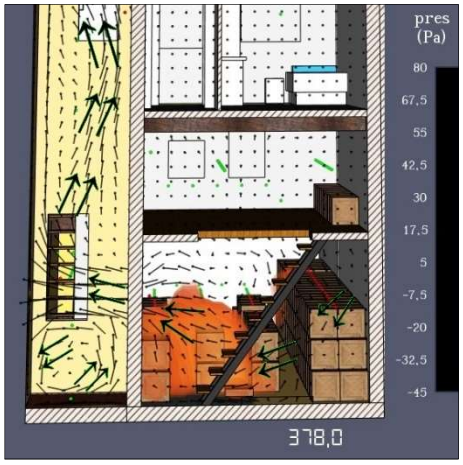


Figure 55. Pressure vectors at t = 378.0s (before the light patio breaks).

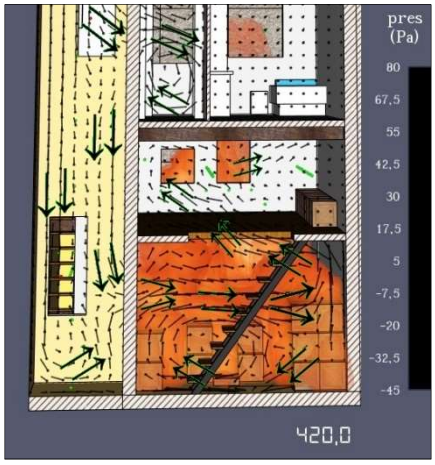
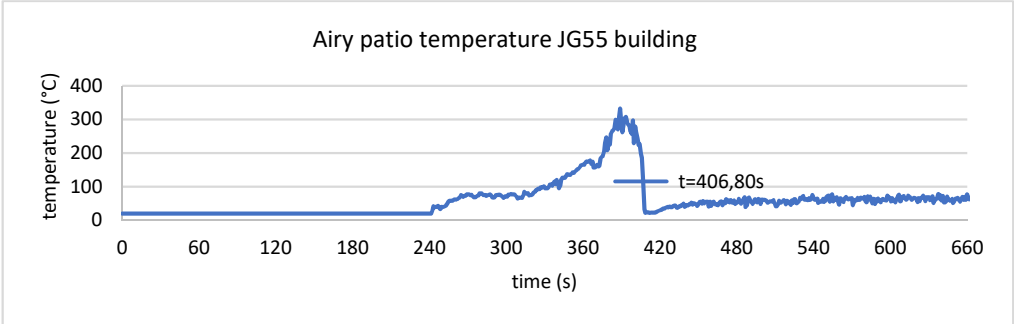


Figure 56. Pressure vectors at t = 420.0s (with light patio open).



Graph 1. Evolution of the temperature inside the small airy patio JG55 at a point 8 meters high.

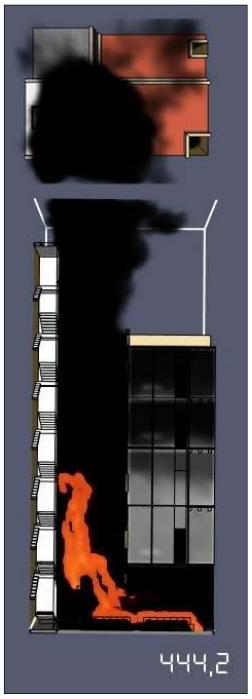


Figure 57. Smoke and flame t=444,2s.

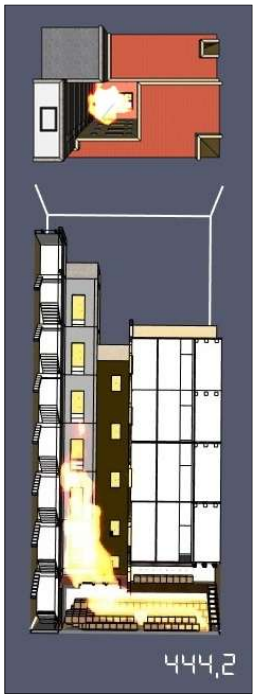


Figure 58. Flame t=444,2s.

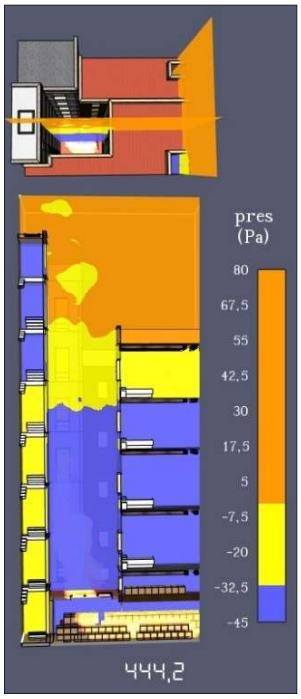


Figure 59. Pressure and flame t=444,2s.

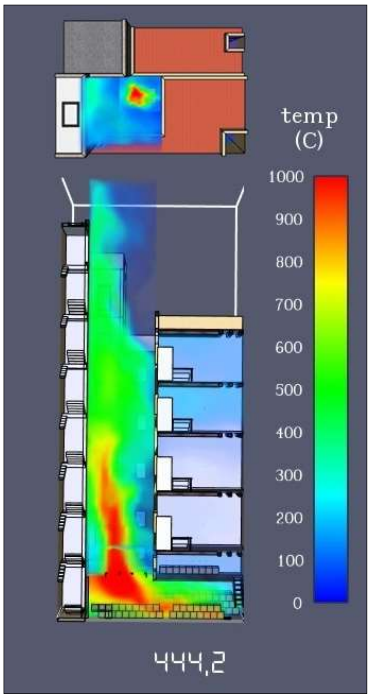


Figure 60. Temperature t=444,2s.

444,2s **Flashover occurs on the 2nd ground floor** causing the exit of smoke and flames with virulence through the light patio. The neutral pressure plane is maintained at roof level. The beams of the ground floor closer to the light patio are structurally affected.

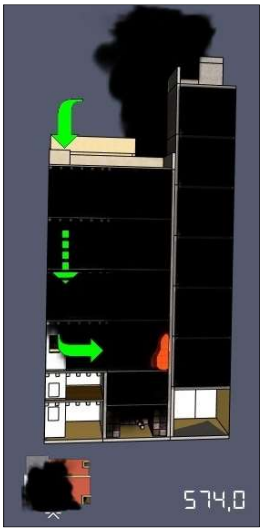


Figure 61. Smoke and flame t=574,0s.

Figure 62. Flame t=574,0s.

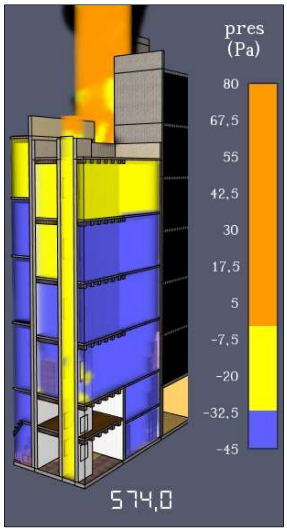


Figure 63. Pressure and smoke t=574,0s.

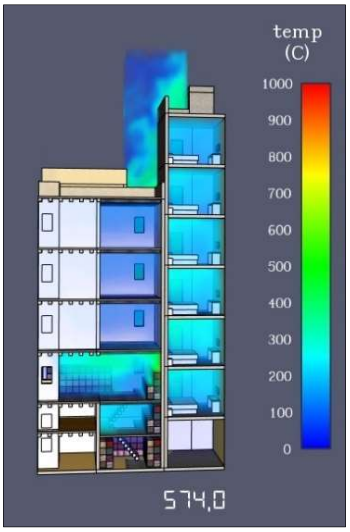


Figure 64. Temperature t=574,0s.

574,0s **Flashover occurs on the first floor of the CM building** when the window that connects to the small airy patio JG55 is broken. As in the case of JG55, the air enters through the small airy patio and smoke and flames go out through the windows overlooking the light patio.

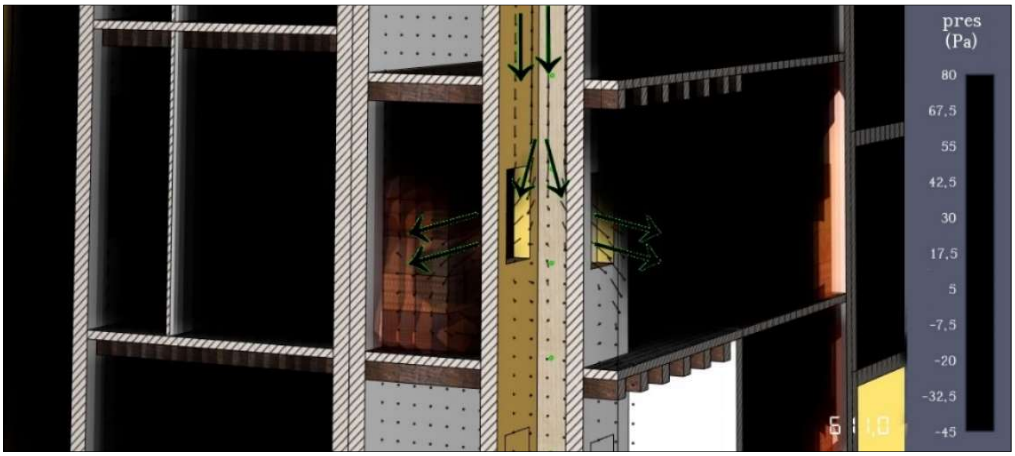
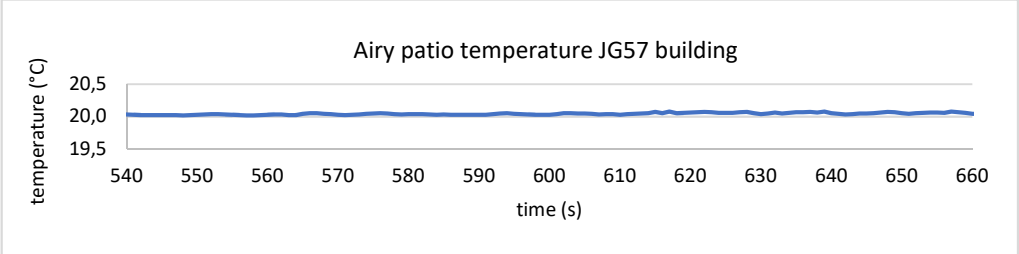


Figure 65. Pressure vectors with window breaking at t = 611.0s.

The temperature variation inside the small airy patio of JG57 is minimal because the clean air that circulates comes directly from the outside and does so at ambient temperature.



Graph 2. Evolution of the temperature at the outlet of the small airy patio JG57 (18 meters high).

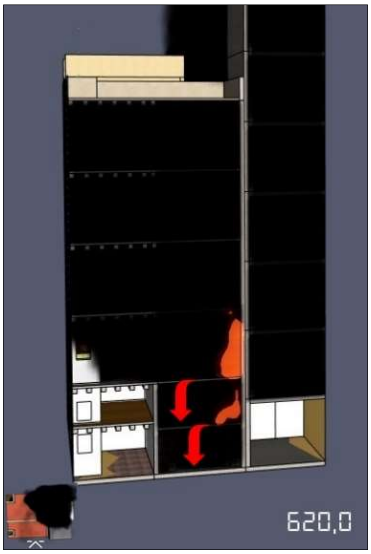


Figure 66. Smoke & flame t=620,0s.

Figure 67. Flame t=620,0s.

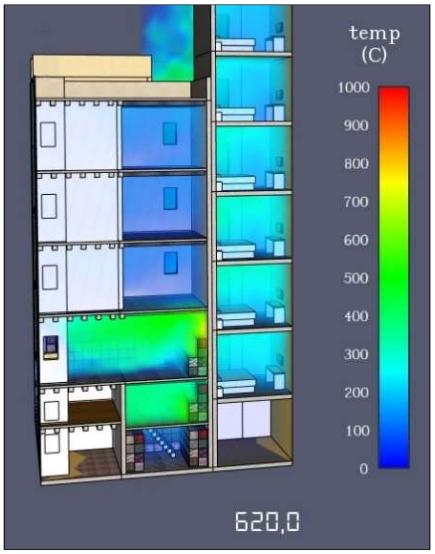


Figure 68. Temperature t=620,0s.

620,0s The fire then spreads down the stair hole, initiating **flashover on the loft and on the ground floor of the CM building**. The stairwell vault fell during firefighting operations without being injured.

Figure 69. Smoke & flame t=660,0s.

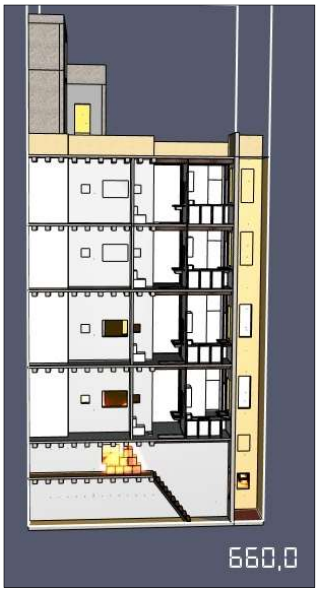


Figure 70. Flame t=660,0s.

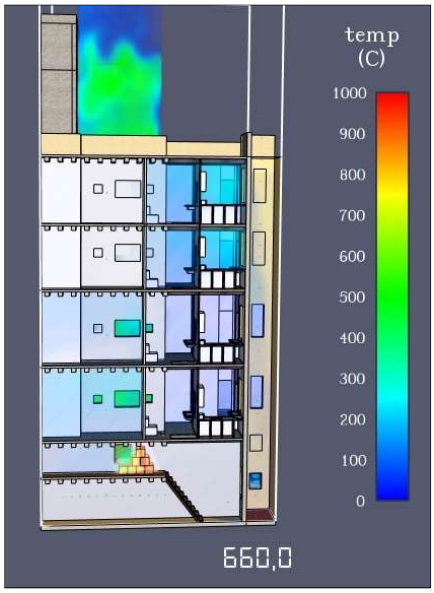


Figure 71. Temperature t=660,0s.

660,0s **Flashover occurs on the loft 1st of the JG55** building, spreading to the ground floor with which it communicates directly.

END OF THE SIMULATION

From this point on, numeric instabilities occur and significant fluctuations in temperature and pressure values that do not correspond to the actual physics of a fire. For this reason, having obtained consistent results to this point, the simulation is ended.

Notwithstanding this, beyond the 660 seconds of simulation there is a flashover on the 3r2a and 4t2a kitchens of the JG55 building. However, this does not happen despite being consistent with the temperature values recorded inside the flats.

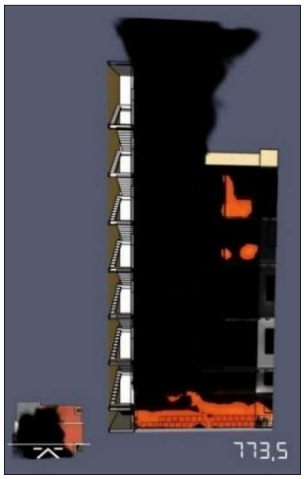


Figure 72. Smoke & flame t=773,5s.

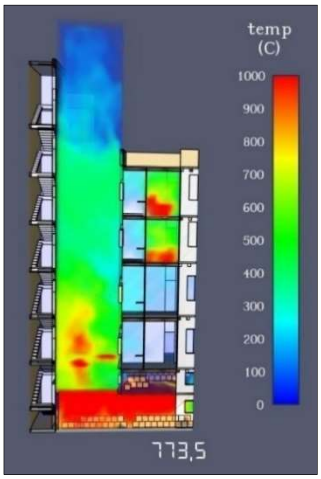
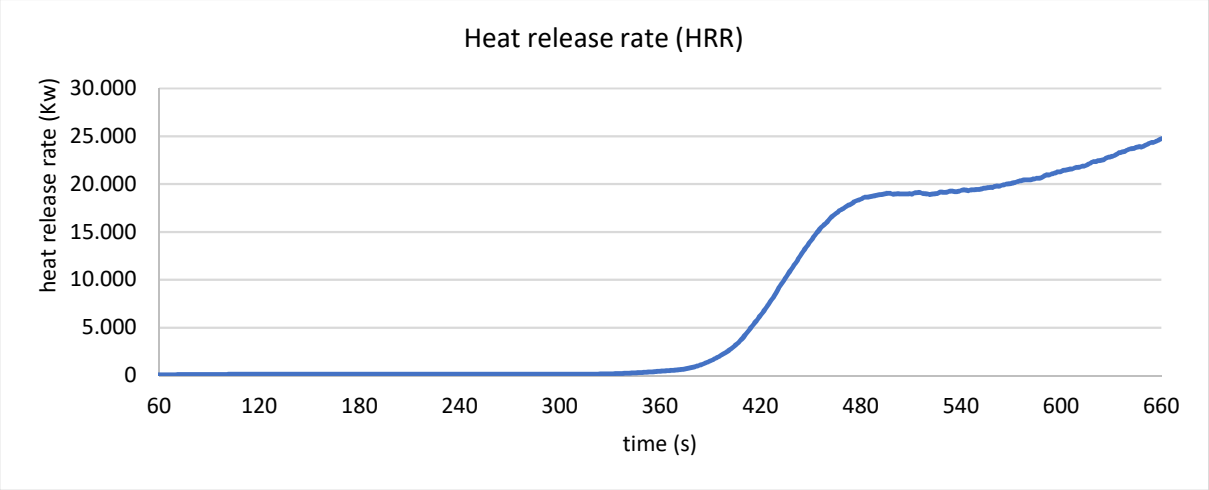


Figure 73. Temperature t=773,5s.

Fire behavior pattern

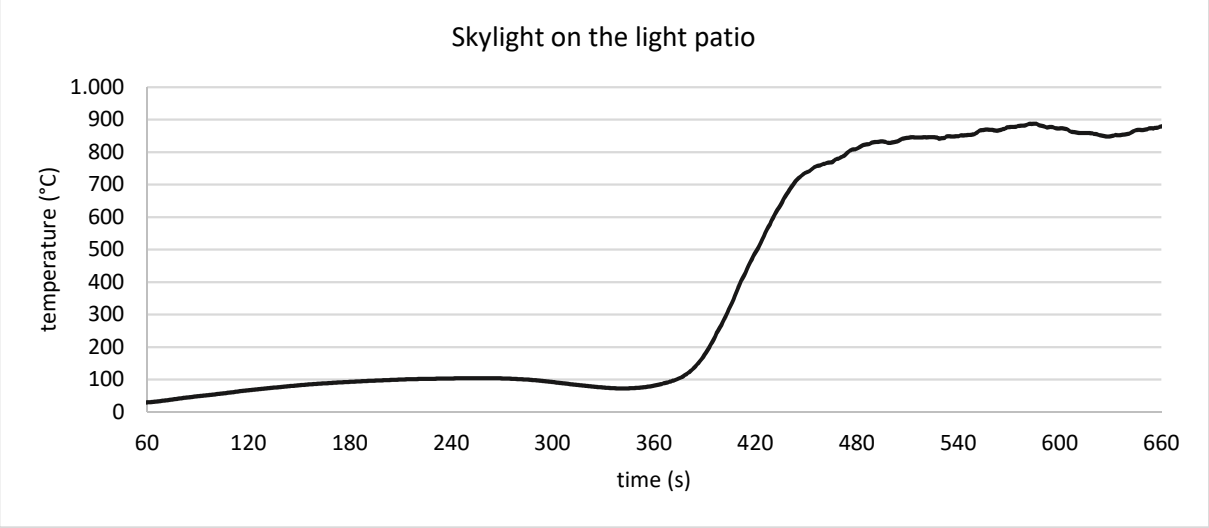
The fire originates at the ground floor of JG55 building, where at the time of the fire all doors and windows were closed. The temperature inside the enclosure increases and the volume expansion of the gases generates an overpressure of 12 Pa, which represents a force of about 1.2 kg/m².

During the first five minutes (300s) most of the heat generated is lost by the conduction through the walls, as we see in Graph 3, where it almost does not increase and remains constant.



Graph 3. Graphical representation of the HRR parameter using a moving average trend line. The mobile line smooths out data variations, showing the trend more clearly.

At the same time, note that the temperature curve in Graph 4 begins to decline because of low oxygen levels. At this moment, it's a ventilation limited fire.



Graph 4. Temperature in the skylight located 2.30 meters high and centered on the light patio plant view.

The breaking of the window overlooking the small airy patio JG55 alters the ventilation; increases the supply of oxygen to the combustion, increases the rate of heat release and raises the temperature through the flashover. From minute five to minute six (360 to 480s) the temperature rises from 100°C to 800°C while a fire is fuel controlled. The temperature is maintained until the end of the simulation with variations of ± 100°C and a maximum value of 987°C.

Thermal analysis

The following are different graphs of temperatures obtained using FDS. Time is represented on the abscissa axis and temperature is on the ordinate axis. The line colors of each graph correspond to the legend image on the right side of each graph. Figure 74 shows a plant view about the situation of each column of thermocouples under analysis.

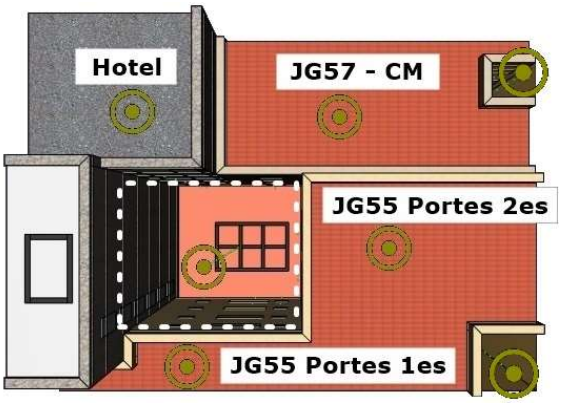
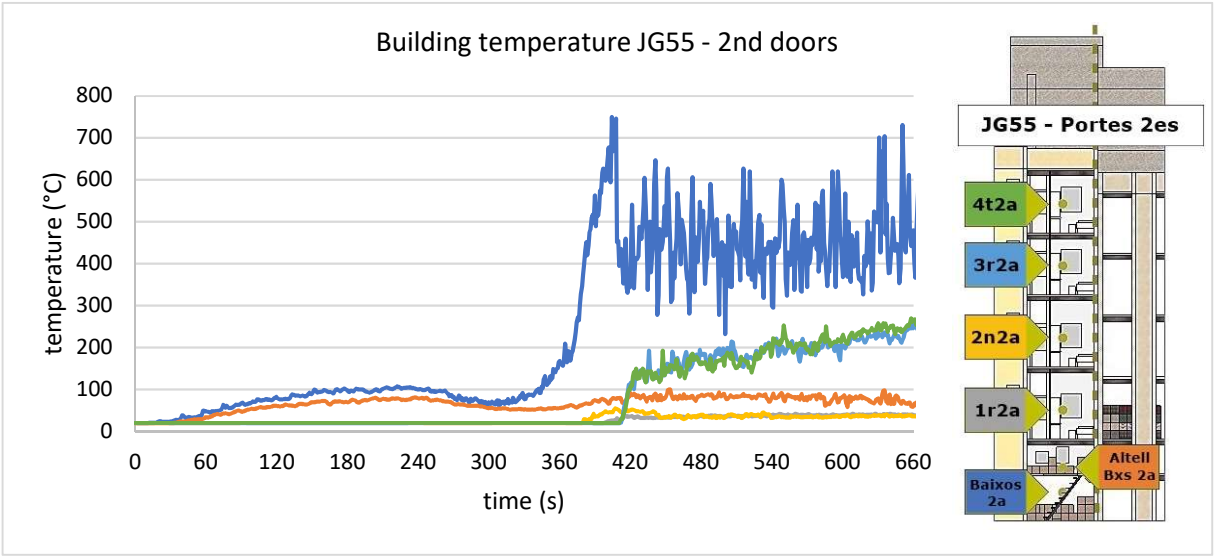


Figure 74. Thermocouples situation plant view.

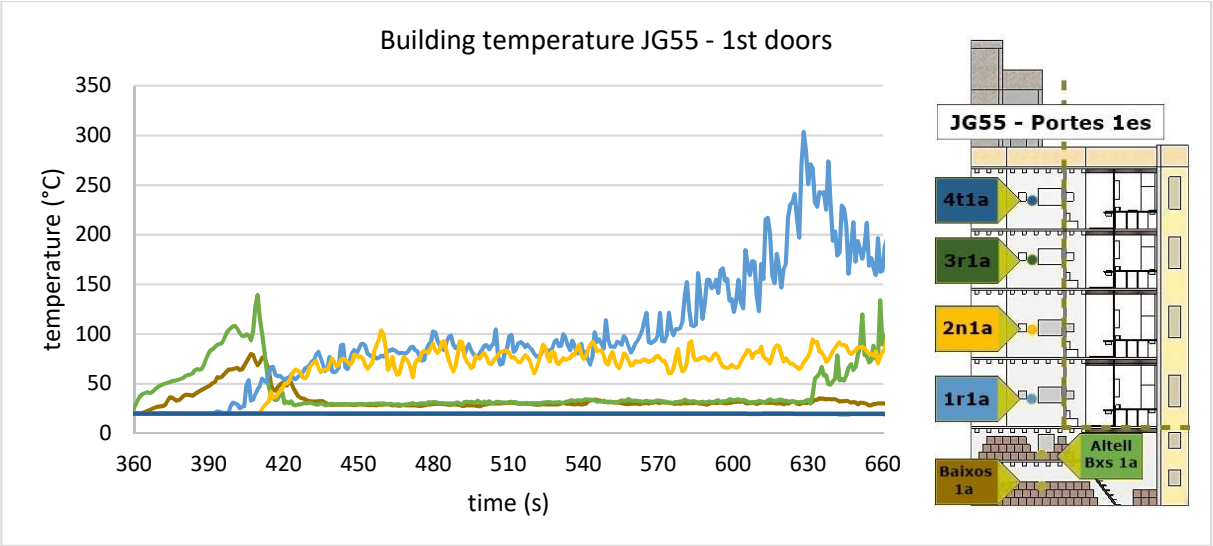
As we saw in Graph 4, the maximum temperature is given to the light patio that communicates the second ground floor with the light patio. However, the maximum temperature in the light patio is 783°C, measured at a separate point with respect to the trajectory of the flow of gases and flames coming through the light patio.



Graph 5. Ambient temperature monitoring in the second ground floor and in each of the second doors of the JG55 building.

The distribution of temperatures from highest to lowest is the following: 783°C at 2nd ground floor, 269°C at 4th 2nd, 258° at 3rd 2nd, 100°C at loft, 55°C at 2nd 2nd and 42°C at 1st 2nd.

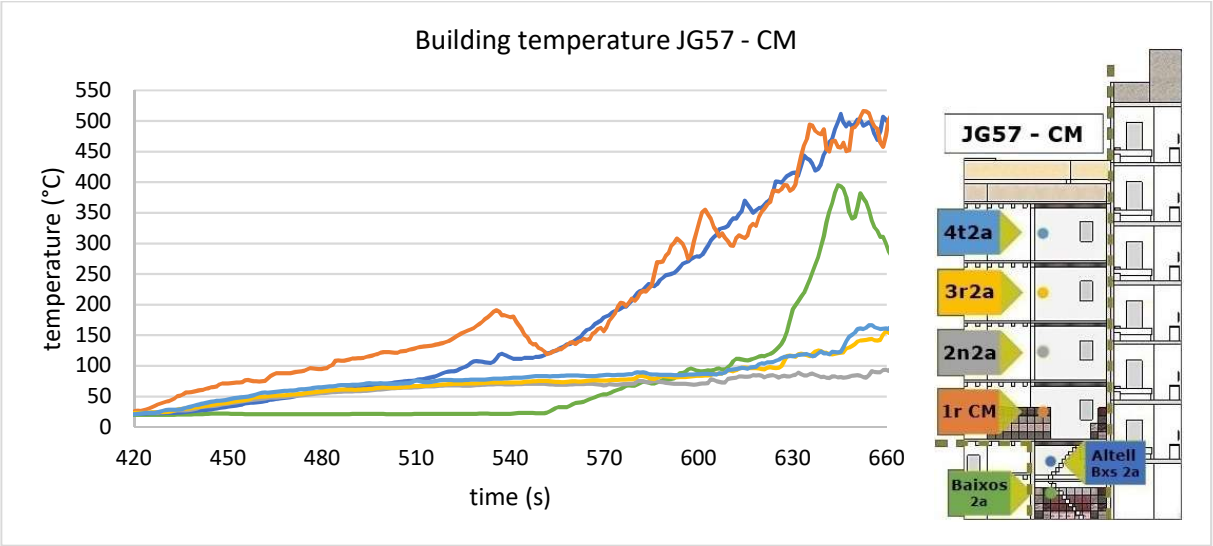
There is a stratification of the temperature of the different floors around two strips with similar values. On the one hand the 1st and 2nd floors (42-55°C), and on the other the 3rd and 4th floors (258-269°C). The loft area, despite communicating with ground floor, has maximum temperature of 100°C.



Graph 6. Ambient temperature monitoring in the first ground floor and in each of the first floor doors of the JG55 building.

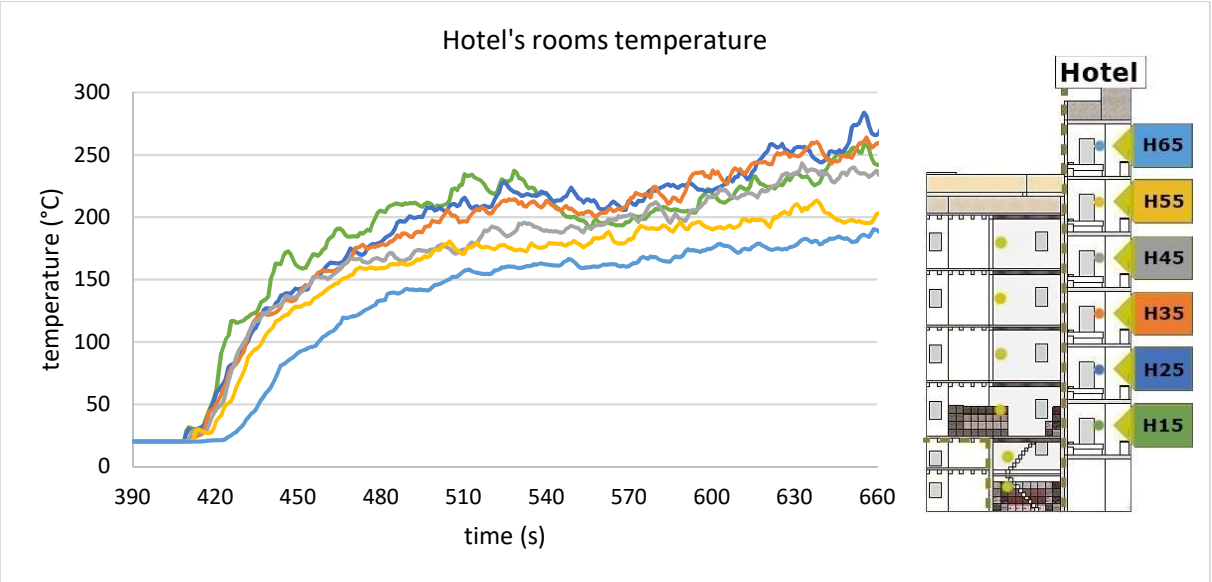
As for the first doors, the highest temperature values are in the 1st floor with 303°C. It is known that this floor reached the fire situation developed, compatible with the temperatures reached. However, the simulation does not occur as it was not foreseen to put combustible furniture inside.

No change in temperature is detected on the 3rd and 4th floor as the windows were not broken and therefore no smoke inside. The distribution of temperatures from highest to lowest is the following: 303°C in the 1st, 103°C in the 2nd, 139°C in the loft and 80°C in the ground floor.



Graph 7. Ambient temperature monitoring in the second doors of the JG57 building and in the ground and first floor of the CM building.

The JG57 building has the peculiarity that it gives access to the 2nd, 3rd and 4th floors of the CM building. As in Graph 5, these floors show increasing temperature values in favor of the higher floors with 93°C, 166°C and 157°C respectively. Highest temperature values are in spaces where the textile material is stored and burn completely: 516°C on the first floor, 511°C on the loft and 395°C on the ground floor. The maximum temperature per room ordered from highest to lowest is the following: 1st floor, loft, 2nd ground floor, 4th 2nd, 3rd 2nd and 2nd 2nd.



Graph 8. Monitoring ambient temperature monitoring in the Hotel's rooms.

The hotel building, the most constructively modern, also has windows that open directly to the light patio. These are the rooms "5" on each floor and the windows from protected stairwell. Let's look at the different effects of fire:

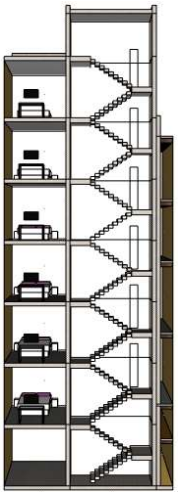


Figure 75. Protected staircase.

Rooms

All of them are affected by smoke and heat without flashover. The maximum temperature in each room ordered from highest to lowest is 339°C at R15, 281°C in R25, 263°C in R35, 243°C in R45, 212°C in R55 and 190°C in R65. There's noticed that the temperature values recorded inside the rooms decrease with height.

If we have a look at Graph 8, R55 and R65 room temperature curves, rooms which stand above the rest of the buildings, are slightly lower than the temperature curves of the other rooms.

Protected staircase

It is the only space in the hotel and the rest of the buildings where light patio windows are not affected by the fire or even by smoke.

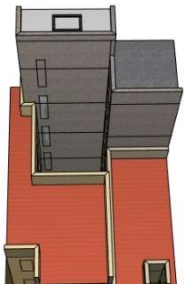
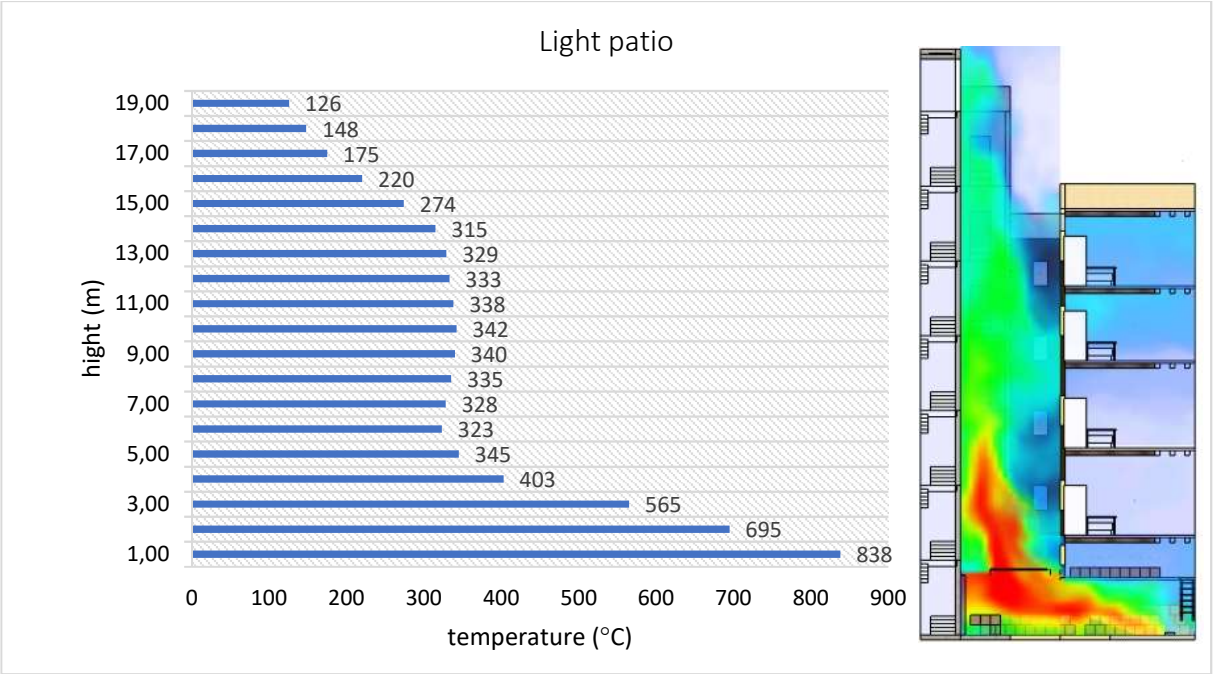


Figure 76. Stair's windows.

In each landing there is a window of 0,50 x 2,20 meters of characteristics EI 60 communicating with the light patio. The result is that none of these windows fail and maintain their integrity. In the simulation are windows that were not linked to any thermocouple precisely because the hypothesis was that they would not be broken, as they did.

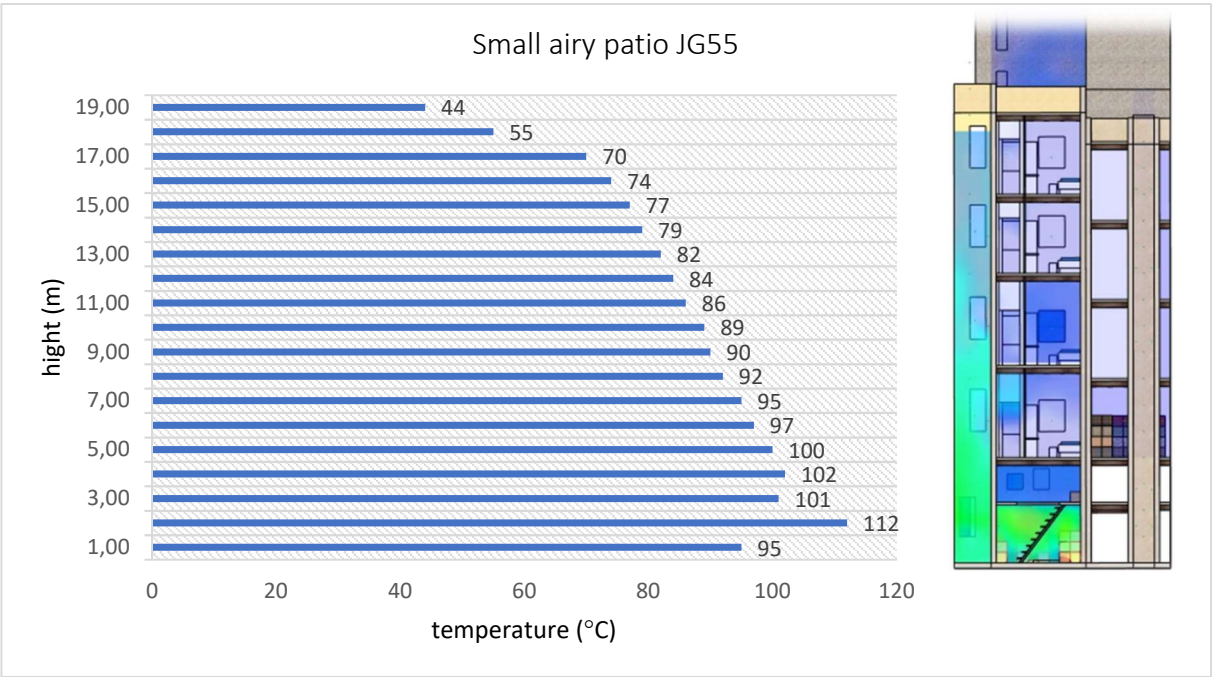
It would have been interesting to place thermocouples equally at each of these points to know the temperatures they reached.

It is worth mentioning that Firefighters made an opening in the glass of the first-floor landing window to extinguish from this point, it is understood that using a fan to generate a positive pressure and that there is no smoke.



Graph 9. Results of the column of thermoparells in the center of the light patio, that are separate one meter between them from the ground of the light patio. It corresponds to the average temperature of the period that goes from 390 to 490s, which coincide with the beginning of the exit of gas and flames through the light patio.

The vertical distribution of temperatures inside the light patio is homogeneous in the central section and it varies at the upper and lower ends, where it decreases and increases respectively.



Graph 10. Results of the column of thermoparells in the center of the small airy patio JG55, that are separate one meter between them. It corresponds to the average temperature of the period that goes from 260 to 360s, just before the reversing the sense of air circulation (see Graph 1).

The vertical temperatures distribution inside the small airy patio decreases with height and keep the different behavior in the upper and lower ends of the same way than the light patio.

CONCLUSIONS

We can see that the main problem that raises in this work, the fire spread across inner courtyards façades of buildings, is a pending issue to be addressed from the regulatory field.

The CTE defines geometric characteristics of fire reaction and resistance that must be met by the facades of buildings. It can be considered from the point of view of fire protection that an airy patio is a set of facing facades. For the purposes of the CTE, however, they are not considered as such and, therefore, they are not required to comply with the considerations that do affect the other facades.

- The effects of the spread of fire within an inner courtyard are of a greater intensity and magnitude than those that occur in open facades in a sufficiently wide exterior space, as has been verified in the cases of Chapter 2 and in the simulation of Chapter 3.

- The chimney effect generated in the inner courtyards shows that the consideration of these enclosures as a facade is not enough to limit the spread of a fire. The breaking of windows of the upper floors caused by the chimney effect is a documented fact in several of the cases studied on Chapter 2.

- The spread of fires across inner courtyard generate a greater impact on all areas of the building, with the corresponding increase in the number of aid requests from people at serious risk. The greater extent of the fire ensures the safe confinement of the rest of the neighbours and the feasibility of carrying out horizontal evacuations.

- The spread of fires across inner courtyards generates scenarios of greater uncertainty for the intervention of firefighters given the difficulties of accessibility.

The simulation using the computer program Fire Dynamics Simulator has allowed us to approach the actual behaviour of the fire by adjusting the programming variables, which we knew from the observation of their effects. The spread of the fire through a light patio of 3.60 x 4.00 x 15.50 m and two small airy patios of 1.40 x 1.40 x 18.20m and 1.00 x 0.800 x 18.20m has been analysed.

As a result of the analysis of the simulations, we can draw the following conclusions:

- The exit of smoke and flames from the fire through the light patio generates a chimney effect that maintains the neutral pressure plan at roof level. The negative pressure generated inside the light patio sucks the flames that come out of the windows generating flame lengths much longer than those that usually take place in open windows in a large enough outdoor space.

- The light patio studied is like a vertical duct completely open at the top. If it had had a light patio -like cover, it would be highly probable that the neutral pressure plane had descended a few meters. With this hypothesis, the effects of pressure and temperature on the upper floor windows would have been more severe.

- The opening of doors and windows during the fire changes the direction of the ventilation pattern by reversing the sense of the air circulation temporarily or permanently depending on the recurrence of these events.

The behaviour of the EI 60 window openings of the hotel's protected stairwell was excellent. The six windows of 0.50 x 2.20m that faced the open space kept their integrity throughout the fire. These characteristics have also been taken into account in the simulation in order to adapt them as much as possible to reality.

The usefulness of the model used for the study has become clear. In this sense, the model can be used in new analyses and research by other researchers to expand technical and scientific knowledge on the spread of fire in airy patios.

Recommendations

Some of these conclusions have led us to make recommendations for the definition of technical and functional parameters on inner courtyards:

- Fire resistance EI 60 must be guaranteed on the entire surface of the façades of the inner courtyards, including the windows and any type of opening that communicates with the inner courtyard. The area occupied by ventilation grills will be excluded, which does not have to exceed the 10% of the total area measured on the façade plan.

- It must be ensured that the required fire resistance on the surface of the facades is maintained despite the layout of facilities, such as cables and pipes, which will be carried out by means of ducts with an EI 60 fire resistance classification.

- A reaction to the fire A2-s1,d0 must be guaranteed of the constructive and decorative elements such as facade coatings.

- Priority must be given to the use of eaves and protruding elements as well as the discontinuous distribution of windows with regards to the vertical to limit the effect of a rising fire on the facades. These strategies should be incorporated into airy patios prescriptions.

- Regulatory changes must be prioritized in inner courtyards given the operational difficulty, which causes a greater extension of fire than in fires on exterior facades. The inner courtyards must be considered as a singular propagation route with its own entity within the CTE DB-SI 2.

Final Reflection

In today's increasingly technological society, the importance of having technical and scientific criteria when making decisions is becoming clear. In the field of fire protection, we must use these criteria in the decisions that are taken in the present, and those that we prevent in the medium and long term. Analyses and proposals based on strictly justified criteria must serve as a guide to establish criteria in the technical decisions taken by public administrations in order to ensure the safety of people in case of a fire.

In recent history we have seen examples of crises in which public administrations and governments have had to take urgent measures in the legislative and economic field to improve the conditions of fire protection from the precedent of a major fire in a building. The field of fire protection can also be a critical issue, and even a political one.

In short, "we must see them coming" and act accordingly by taking appropriate preventive action. As technicians, we have economic, ethical, and social responsibilities that should not be shunned; the buildings we build today will mark the fires of tomorrow.

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